

RHIC and the Hunt for the Plasma Brothers

WANTED

DEAD or ALIVE



\$15,000 REWARD

\$15,000 REWARD

Quark & Gluon
Plasma

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Mitchell*

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National
Laboratory*

*Quarknet
Workshop*

7/23/03

The Hunt for the Plasma Brothers: Briefing Outline

- **The Suspect:** The Elusive Quark & Gluon Plasma (QGP) Brothers.

The suspects are known informants.

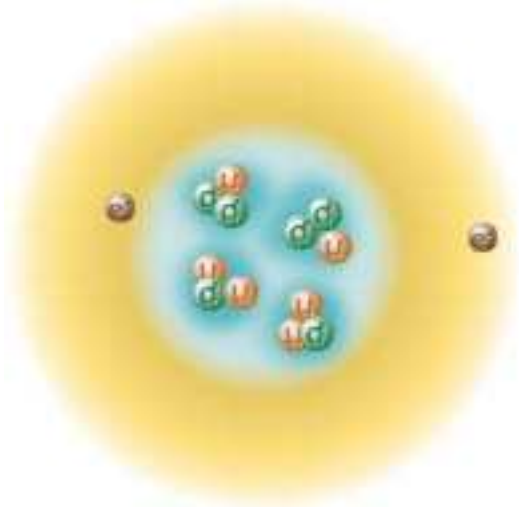
- **The Mission:** Confirm the whereabouts of the QGP brothers and bring in for questioning.
- **Quark Gluon Plasma: Dossier and Modus Operandi**
- **Quark Gluon Plasma: Known Hide-outs**
- **Flushing out the Quark Gluon Plasma**
- **Surveillance Techniques and Results**
- **Current Status of the Hunt**



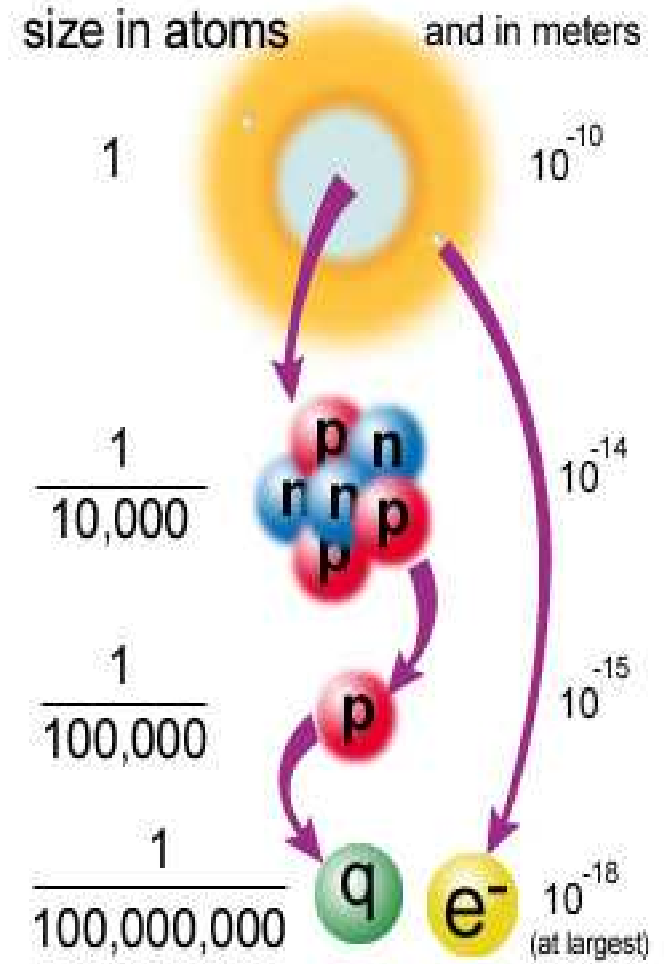
Quark & Gluon Plasma: Dossier

An *atom*
contains a
nucleus...

...which
contains
protons and
neutrons...



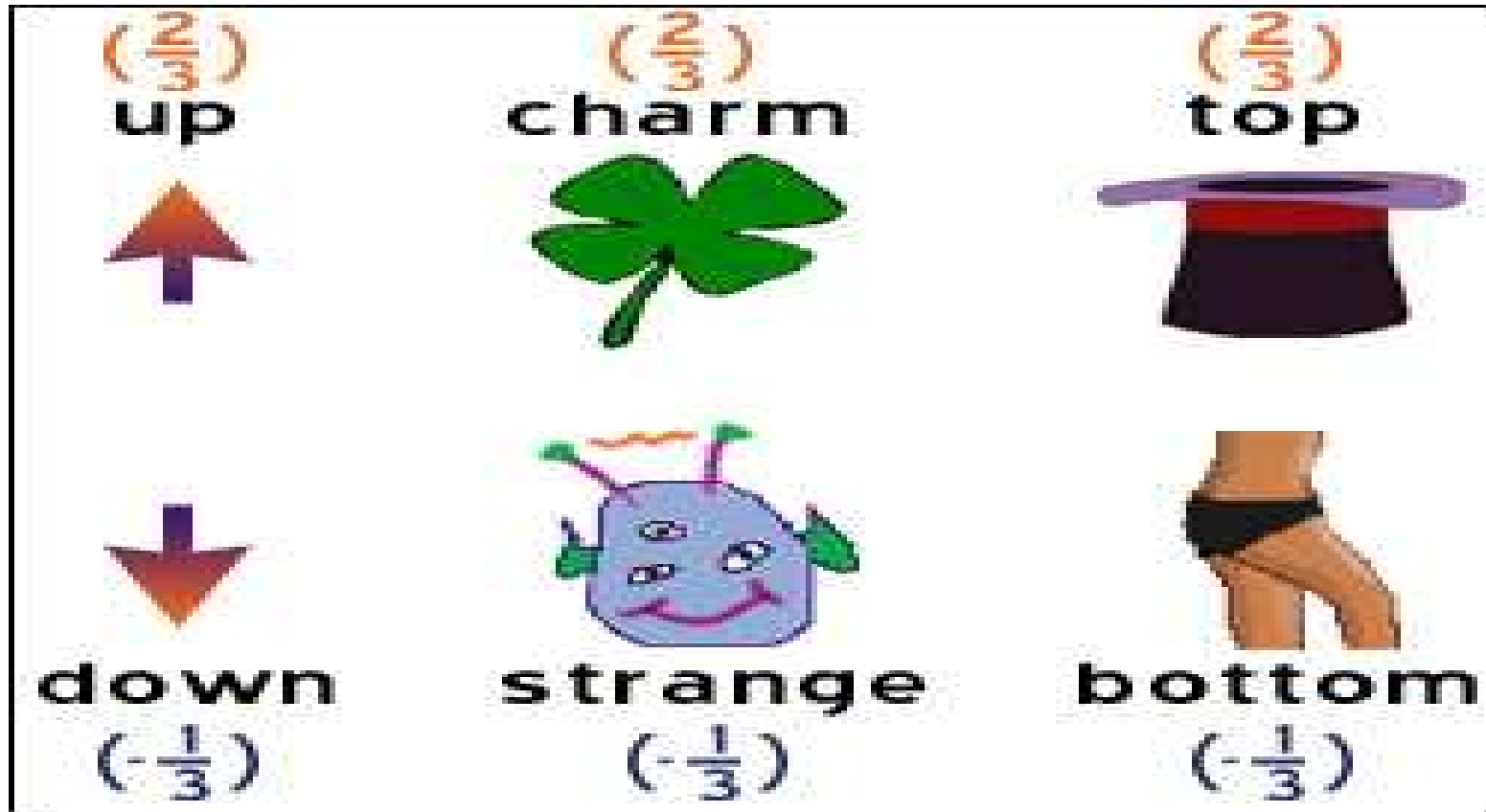
...which
contain *up*
and *down*
quarks.



A Briefing on Quark Brothers



“Nicknames”, or “Flavors”, of Quark Brothers

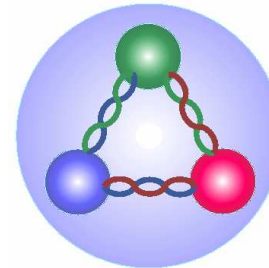


Light and
abundant

Heavier,
harder to
produce

Very heavy,
very rare

Quark & Gluon Plasma Dossier



The QGP is known to use force...



	Gravity	Weak	Electromagnetic	Strong
Carried By	Graviton (not yet observed)	$W^+ W^- Z^0$	Photon	Gluon
Acts on	All	Quarks and Leptons	Quarks and Charged Leptons and $W^+ W^-$	Quarks and Gluons

Quark & Gluon Plasma: Modus Operandi

Quark brothers
always hang out
in gangs of 2's
or 3's (*hadrons*).



... and Gluon
brothers hold
them together...



Creating a Plasma
lets Quark
Brothers roam free
as individuals !!!

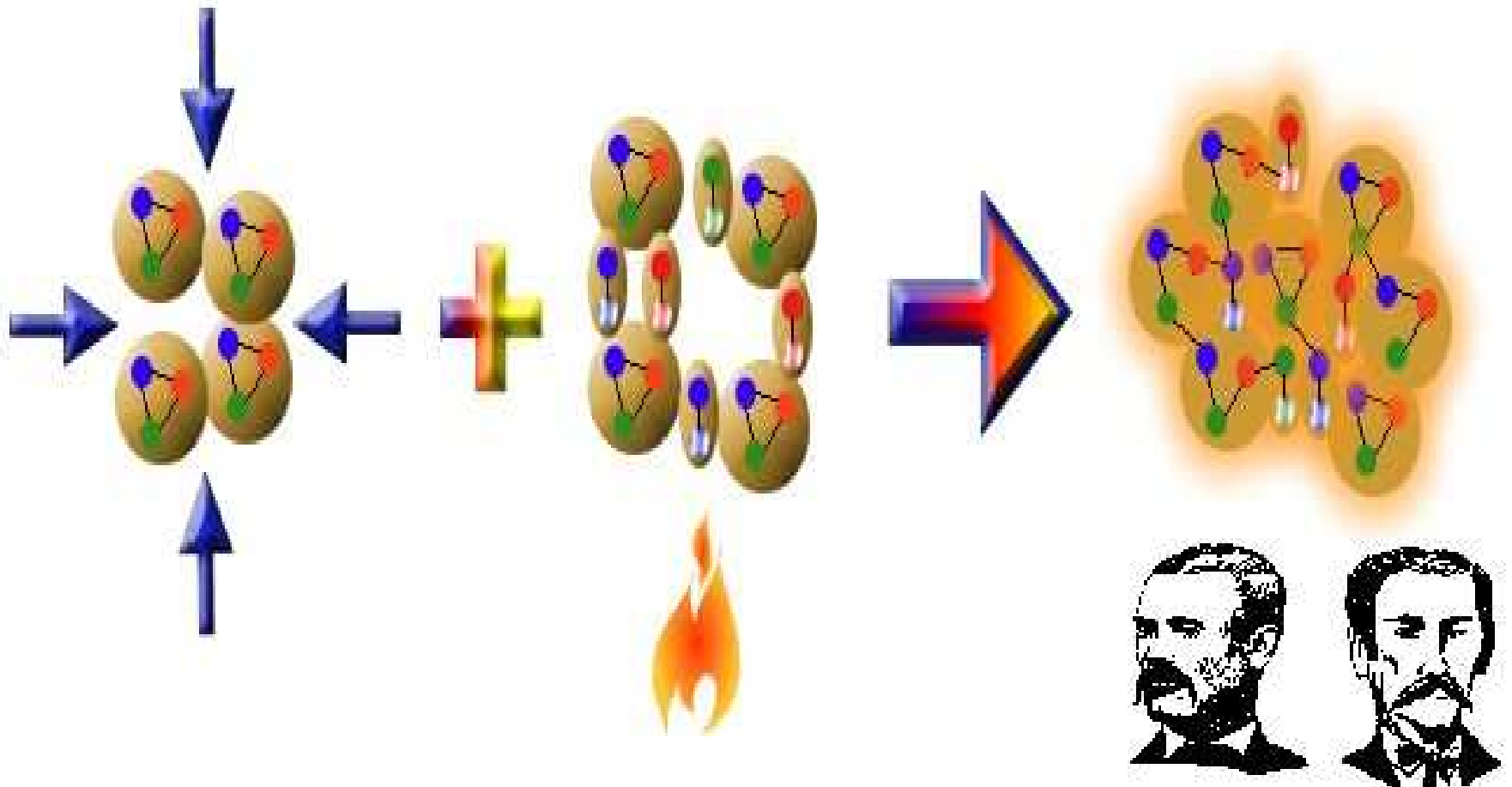
We want to catch
them in the act.

BARYONS = qq \bar{q} *	quarks	electric charge	mass (GeV/c ²)	spin
p proton	u u d	+1	0.938	1/2
\bar{p} antiproton	$\bar{u} \bar{u} \bar{d}$	-1	0.938	1/2
n neutron	u d d	0	0.940	1/2
Λ^0 lambda	u d s	0	1.116	1/2
Ω^- omega	s s s	-1	1.672	3/2
Σ_c sigma-c	u u c	+2	2.455	1/2
Many others !!				

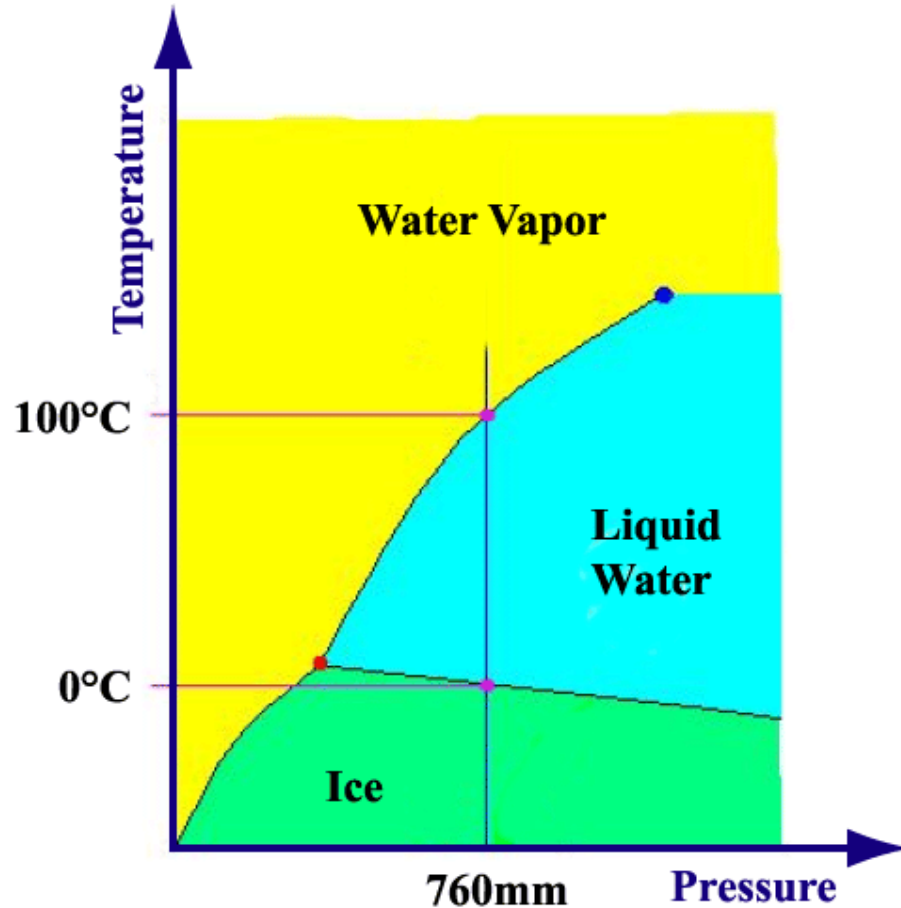
MESON = q \bar{q}	quarks	electric charge	mass (GeV/c ²)	spin
π^+ pion	u \bar{d}	+1	0.140	0
π^- pion	d \bar{u}	-1	0.140	0
K^+ kaon	u \bar{s}	+1	0.494	0
K^- kaon	s \bar{u}	-1	0.494	0
K^0 kaon	d \bar{s}	0	0.498	0
\bar{K}^0 kaon	s \bar{d}	0	0.498	0
ρ^+ rho	u \bar{d}	0	0.770	1
ρ^- rho	d \bar{u}	0	0.770	1
D^+ D	c \bar{d}	+1	1.869	0
D^- D	d \bar{c}	-1	1.869	0
η_c eta-c	c \bar{c}	0	2.980	0

The Strategy: Build our own QGP hide-out and lure the brothers into our trap...

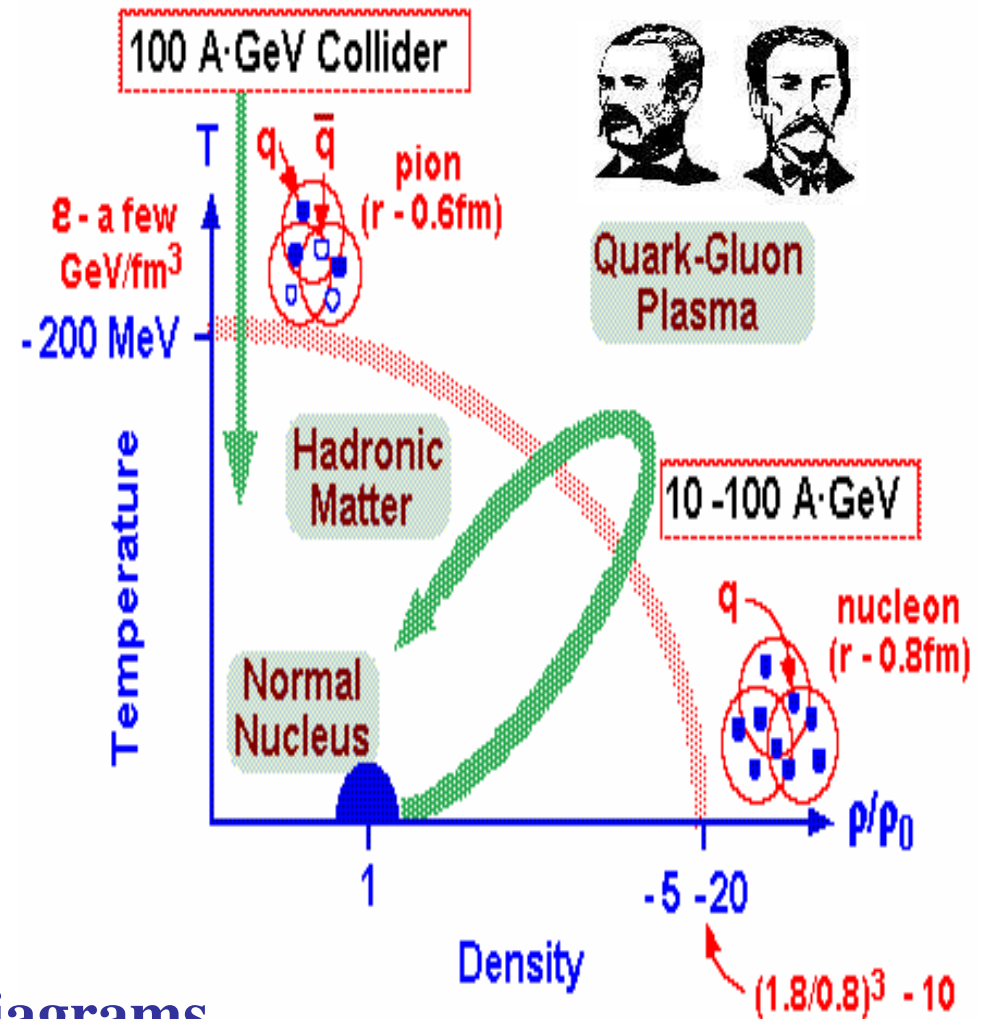
Pressure + Heat (creates pions) → Quark-Gluon Plasma



How to build a QGP Hide-out



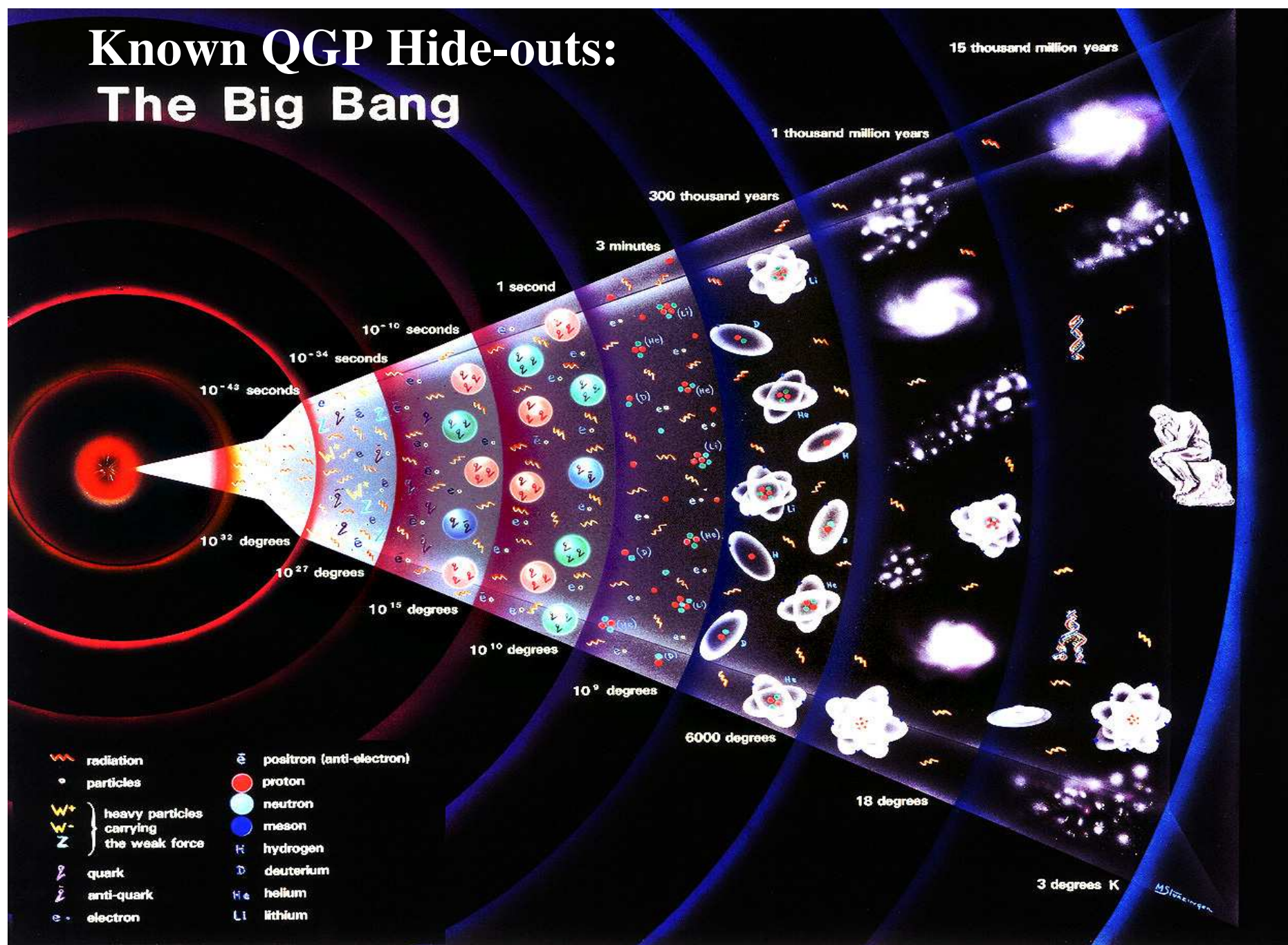
Water



Nuclear Matter

Phase Diagrams

Known QGP Hide-outs: The Big Bang



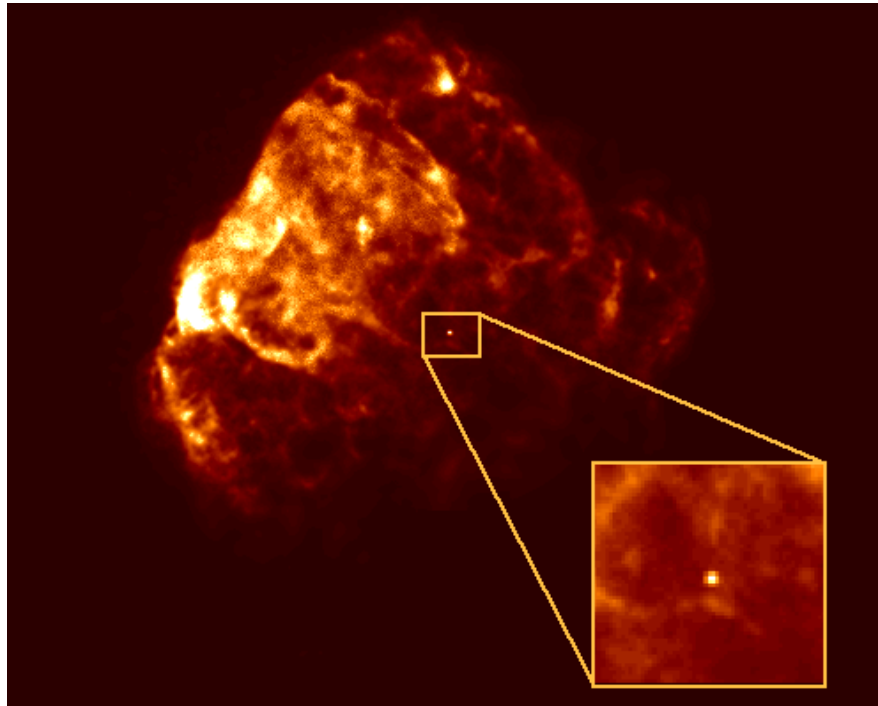
Formation of Hadrons

Large Scale Chromium (second) lattice
simulation - SHR

Formation of Hadrons (detail)

Time-Like Discontinuity (second-order transition)
[Schmitt et al., Nucl. Phys. A 407 (1983) 1-20]
[Schmitt et al., Nucl. Phys. A 407 (1983) 1-20]

Another Possible QGP Hide-Out: The Center of Neutron Stars



Neutron stars are the collapsed cores of a massive star.

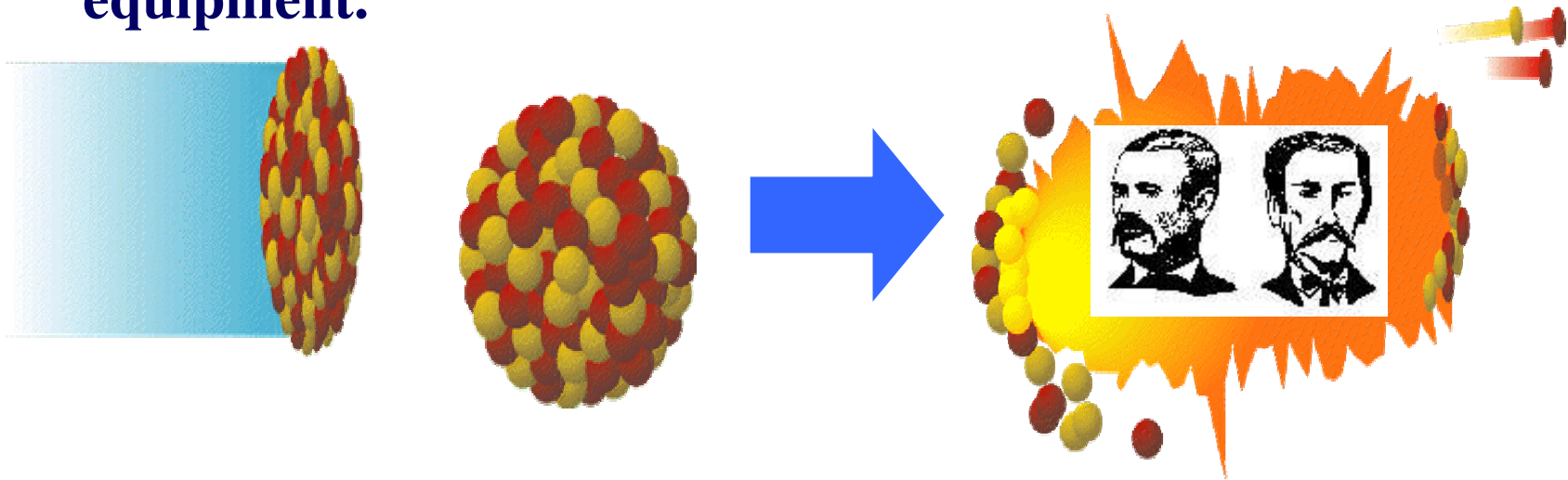
They pack the mass of the sun into the size of a city.



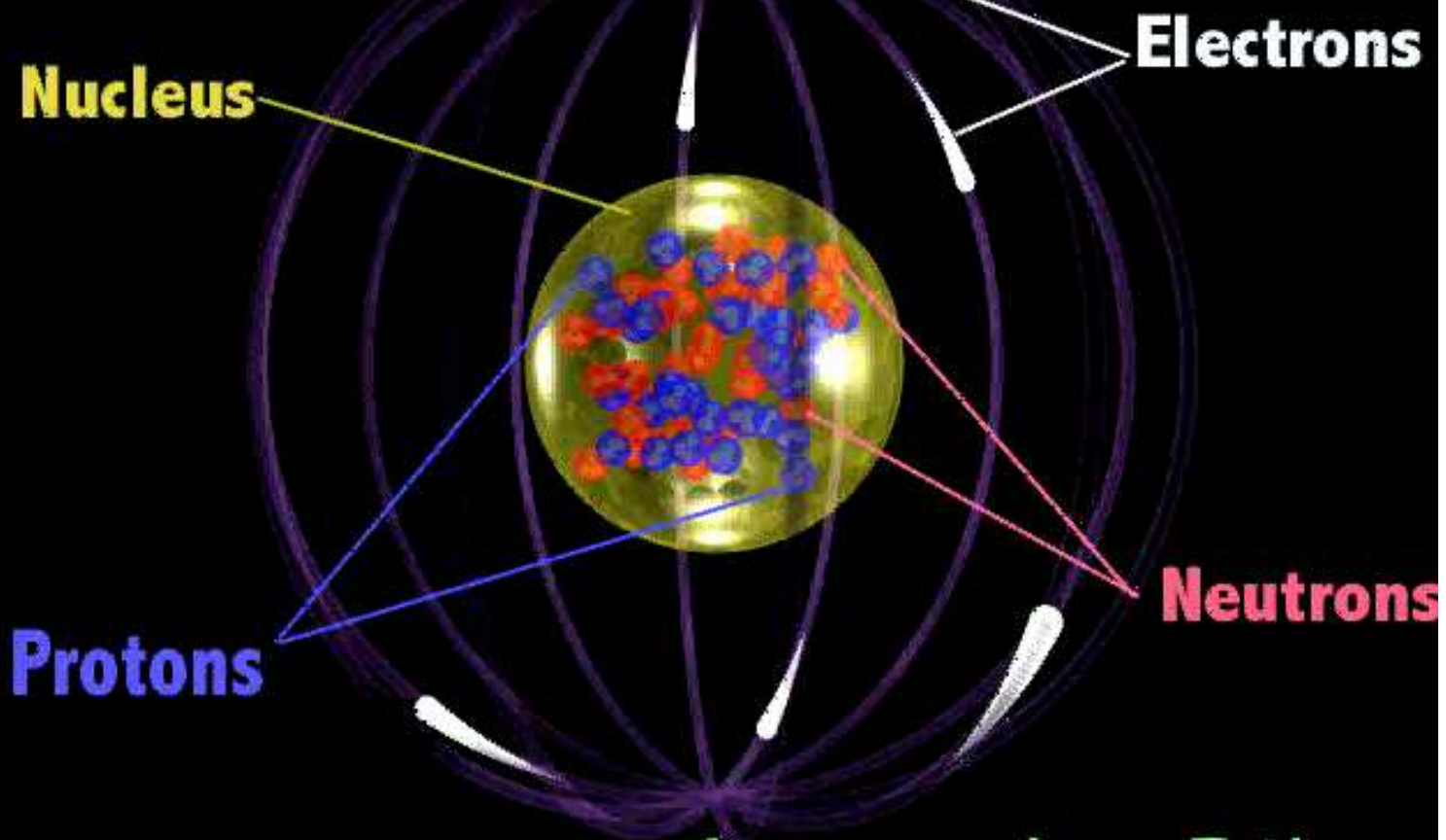
QGP Surveillance Technique

The Plan:

- Take two of the heaviest nuclei we can get our hands on.
- Use a particle accelerator to accelerate them to relativistic speeds.
- Slam them together.
- Surround the collision point with “surveillance” equipment.



Creating a Quark-Gluon Plasma



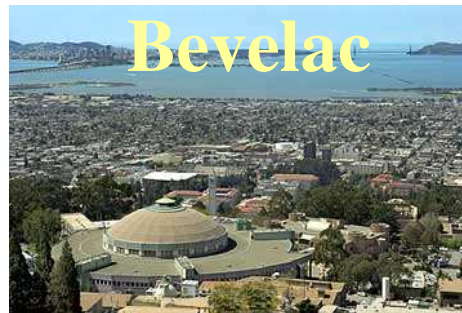
Animation by Jeffery T. Mitchell

Previous Attempts to Catch the Quark-Gluon Plasma.

Laboratory

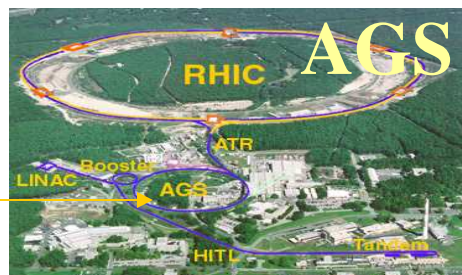
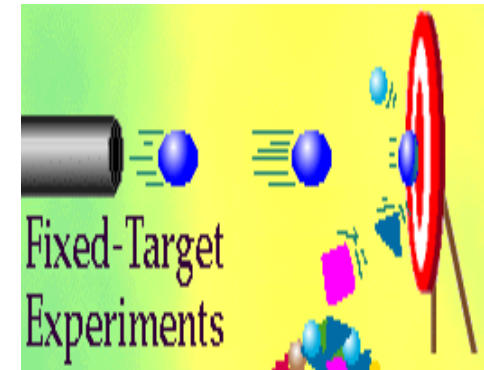


Accelerator



Collisions

**2 GeV/A
Oxygen**



**11.6 GeV/A
Gold**

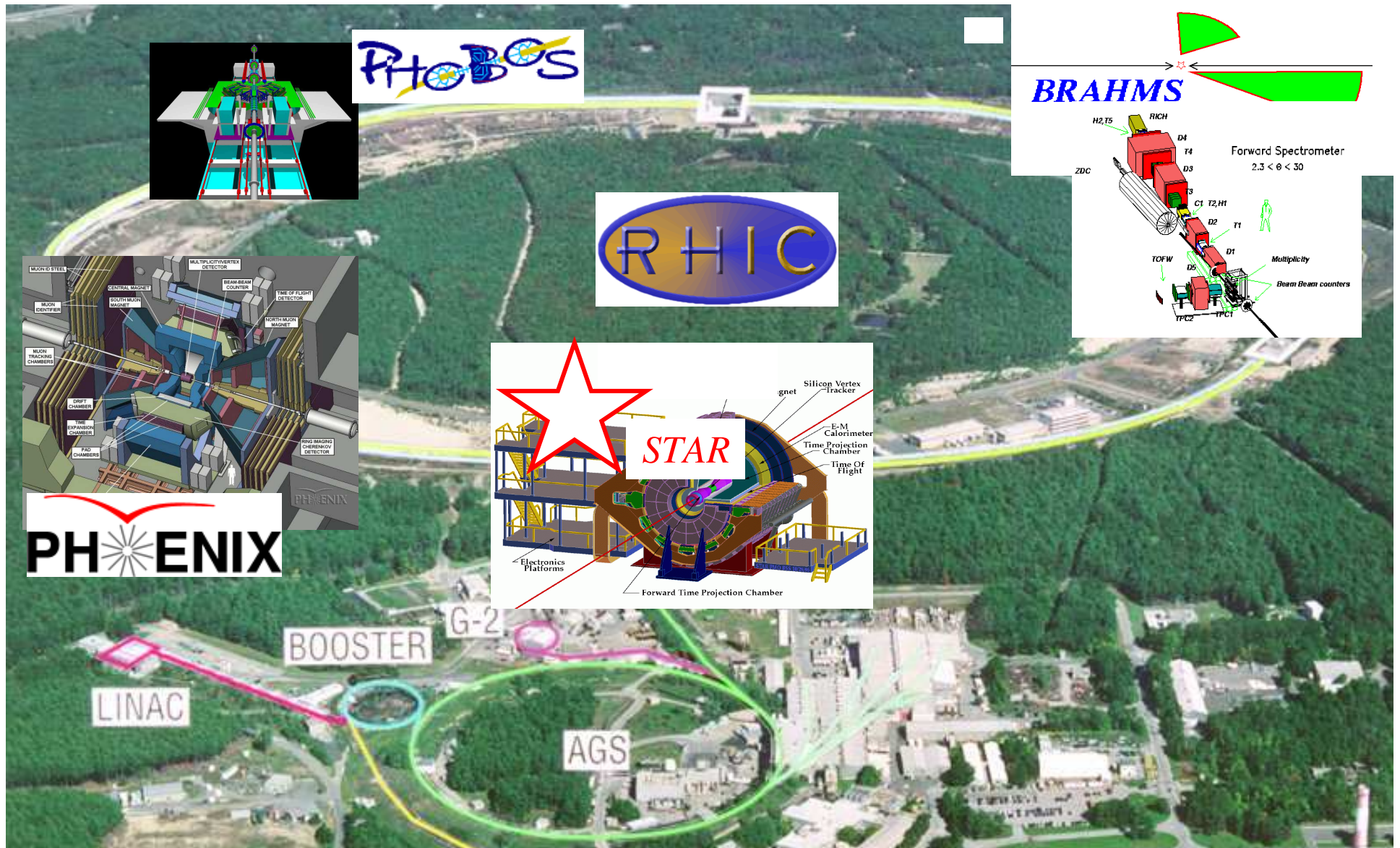


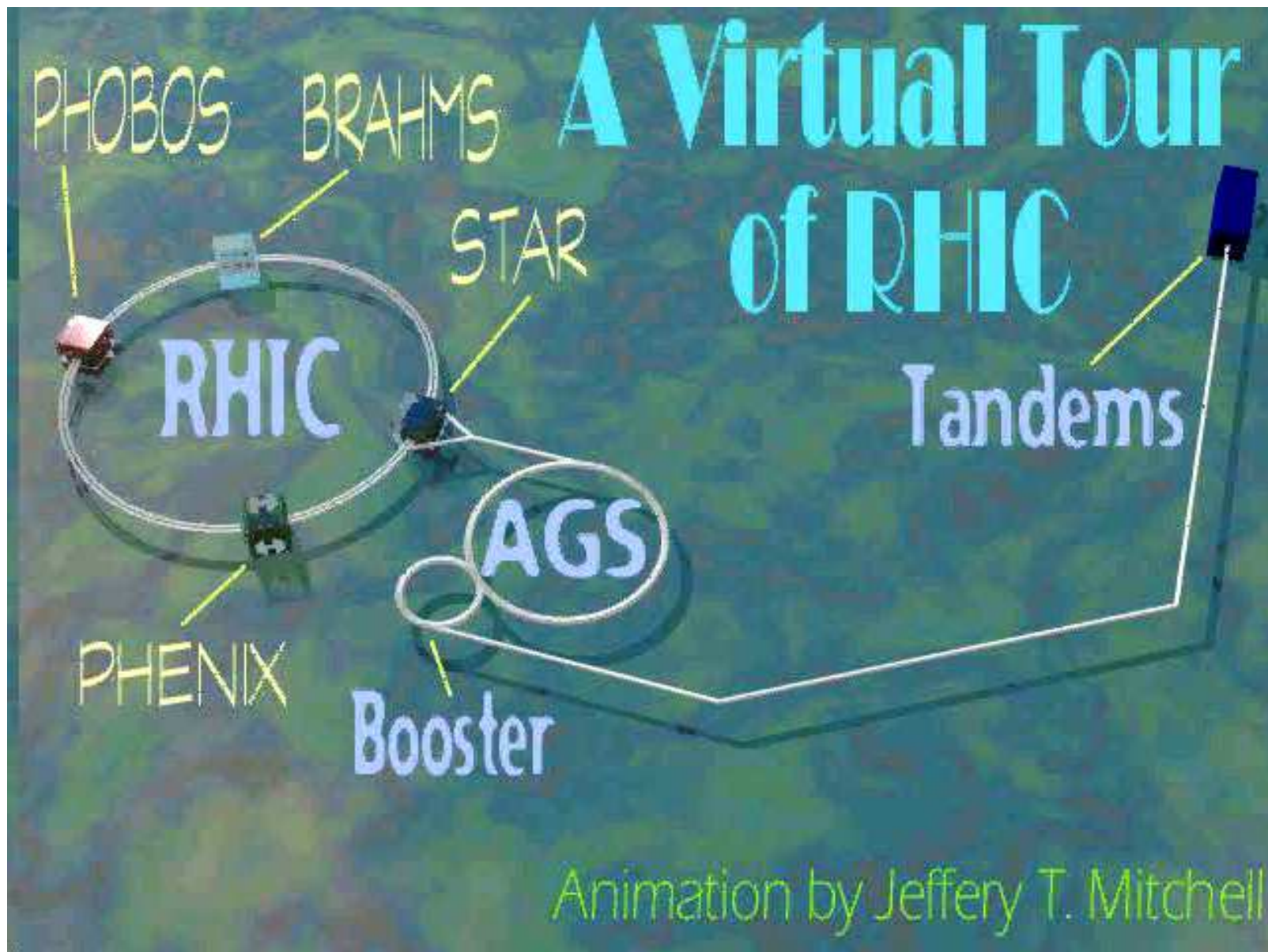
**160 GeV/A
Lead**

**Although we may
have caught
tantalizing
glimpses of the
QGP, the
evidence is not
definitively
conclusive.**

The QGP Hide-Out Complex

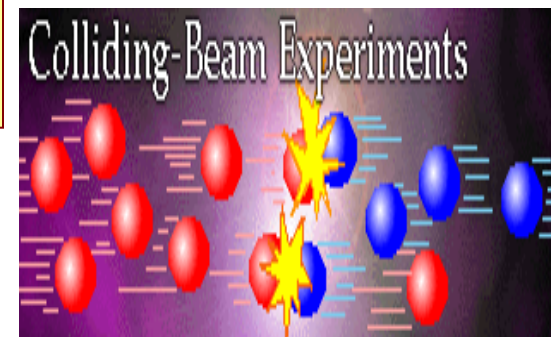
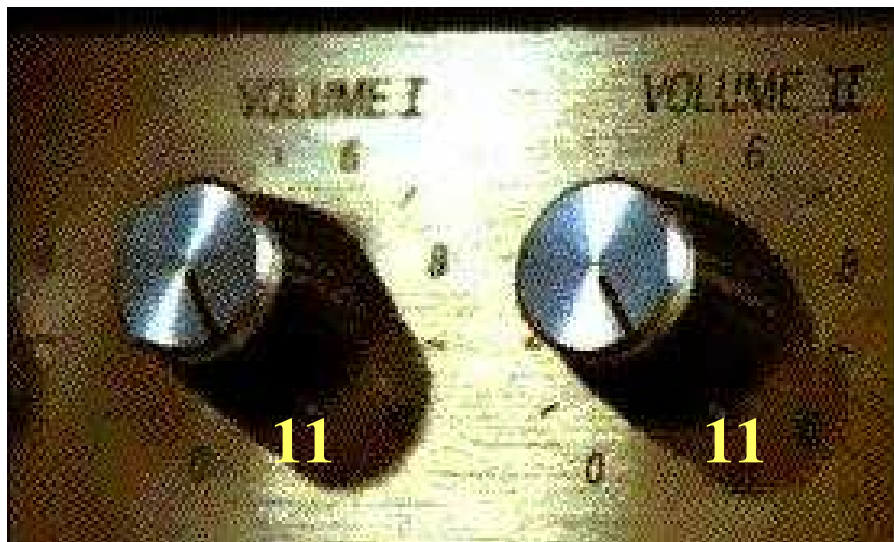
The Relativistic Heavy Ion Collider at BNL





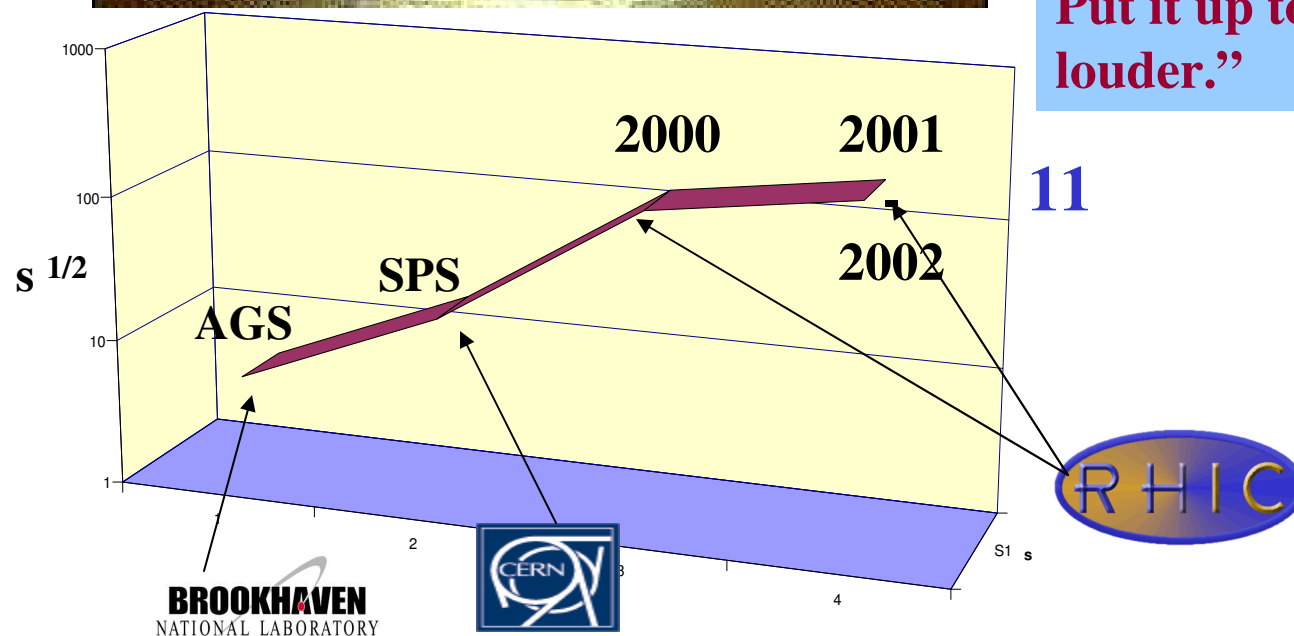
Turning Up The Volume!

(...that is, the collision energy)



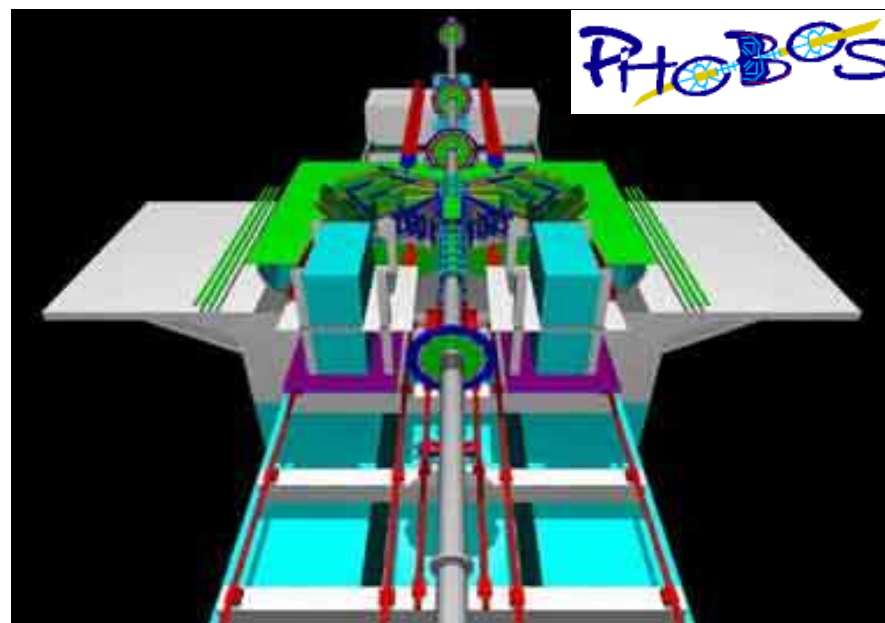
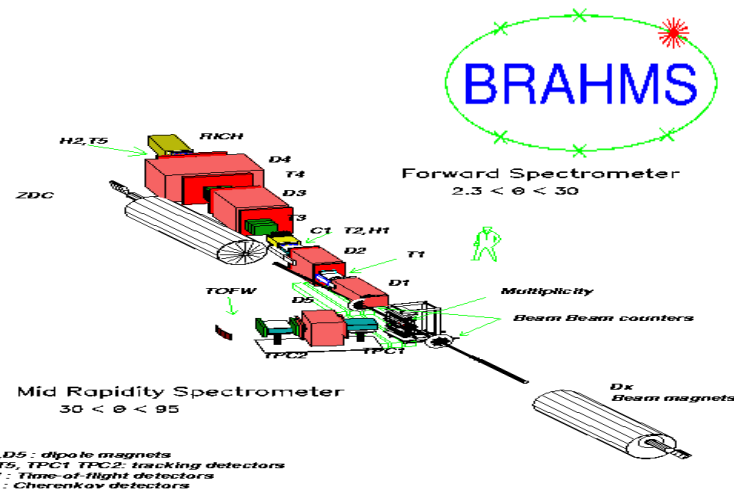
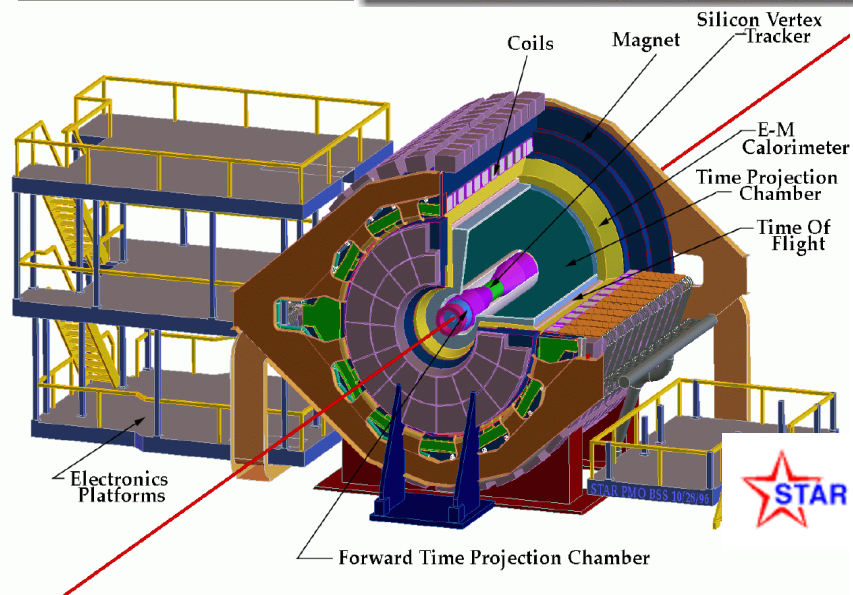
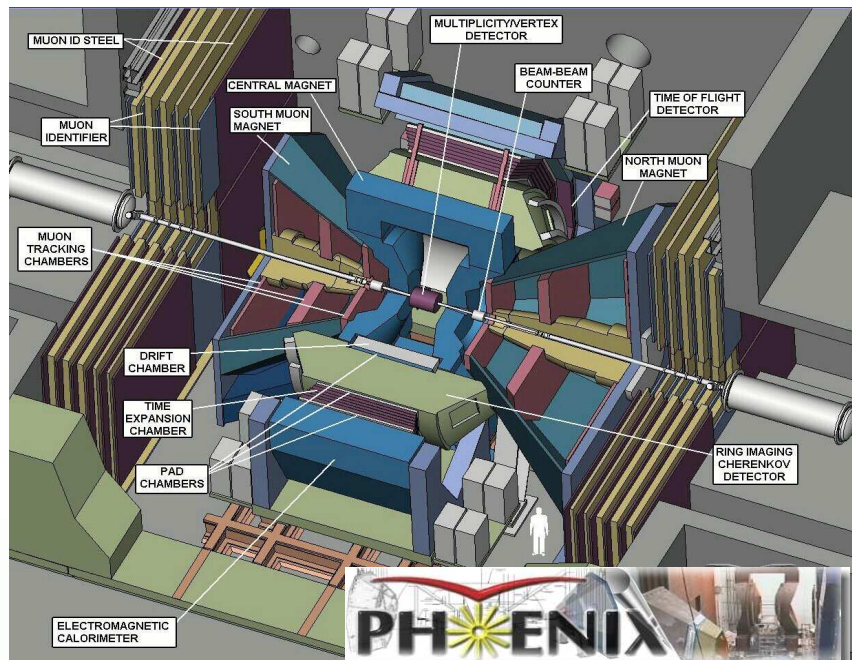
“What we do is if we need that extra push over the cliff...you know what we do?

Put it up to 11. One louder.”

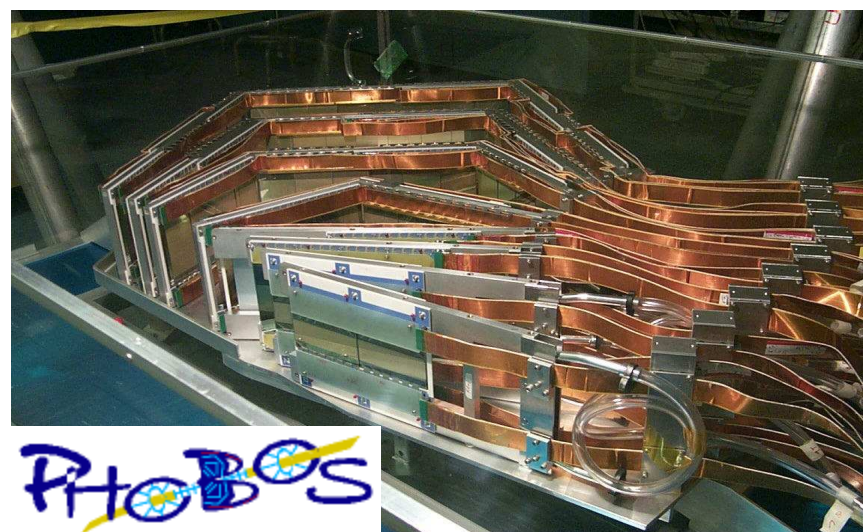
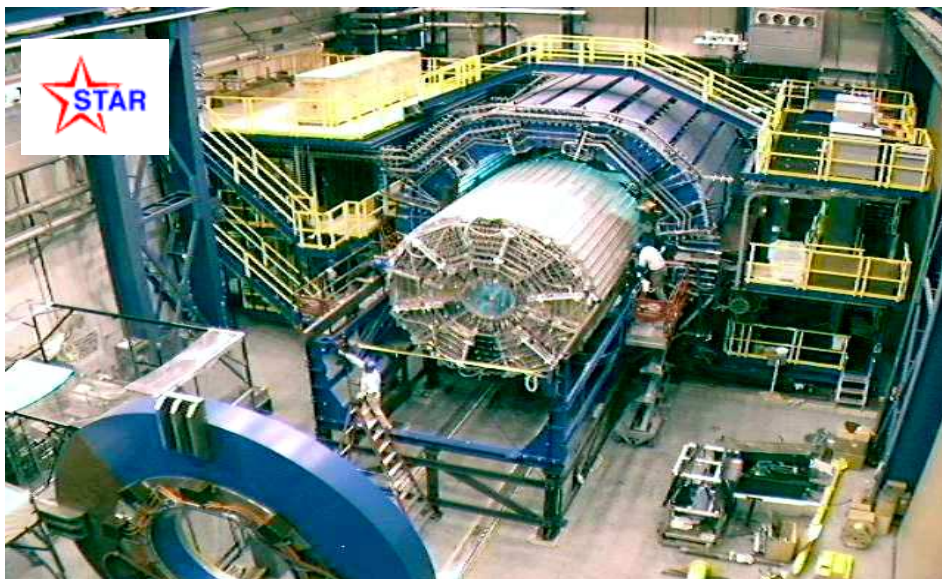
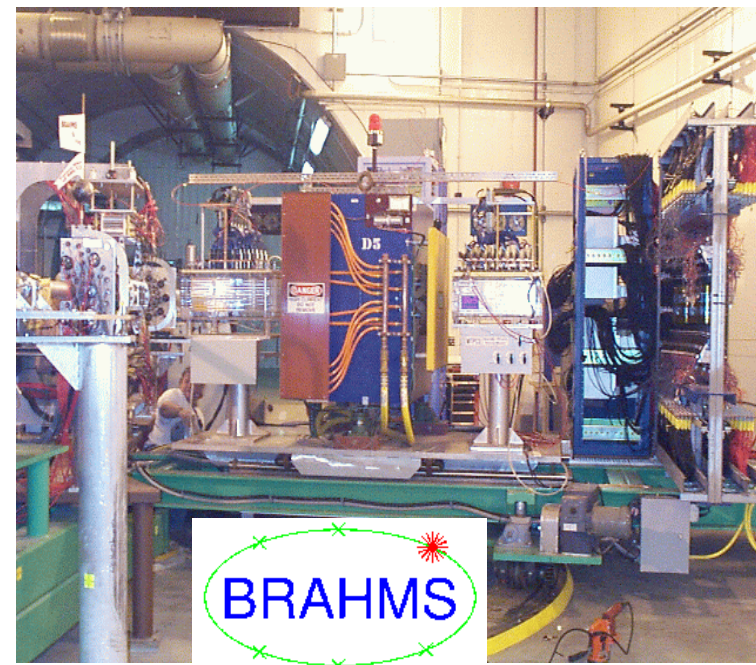


Accelerator “Volume” is quoted as s^{1/2}, which is the energy available for particle production

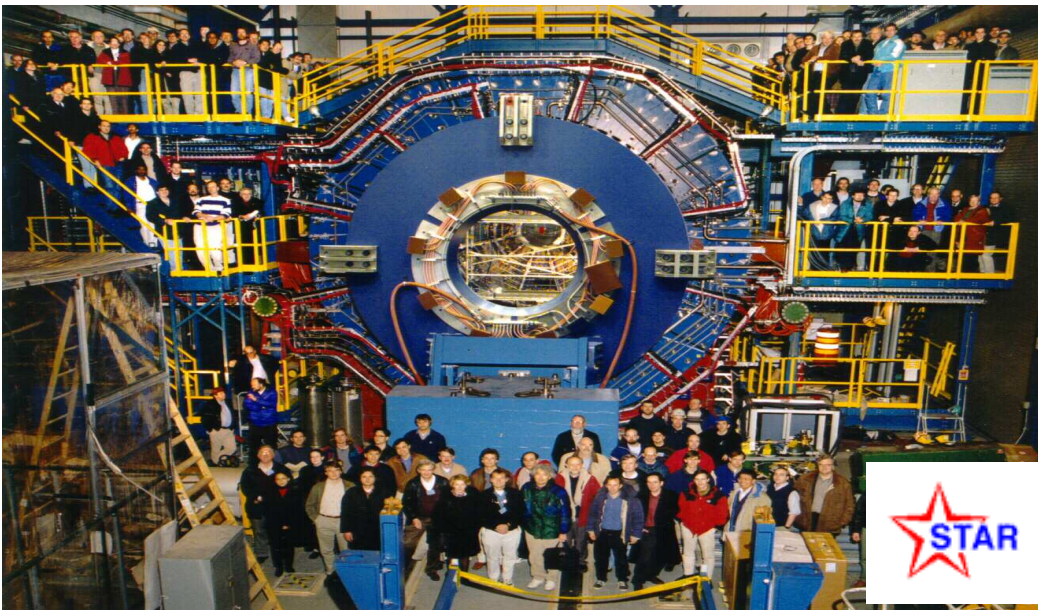
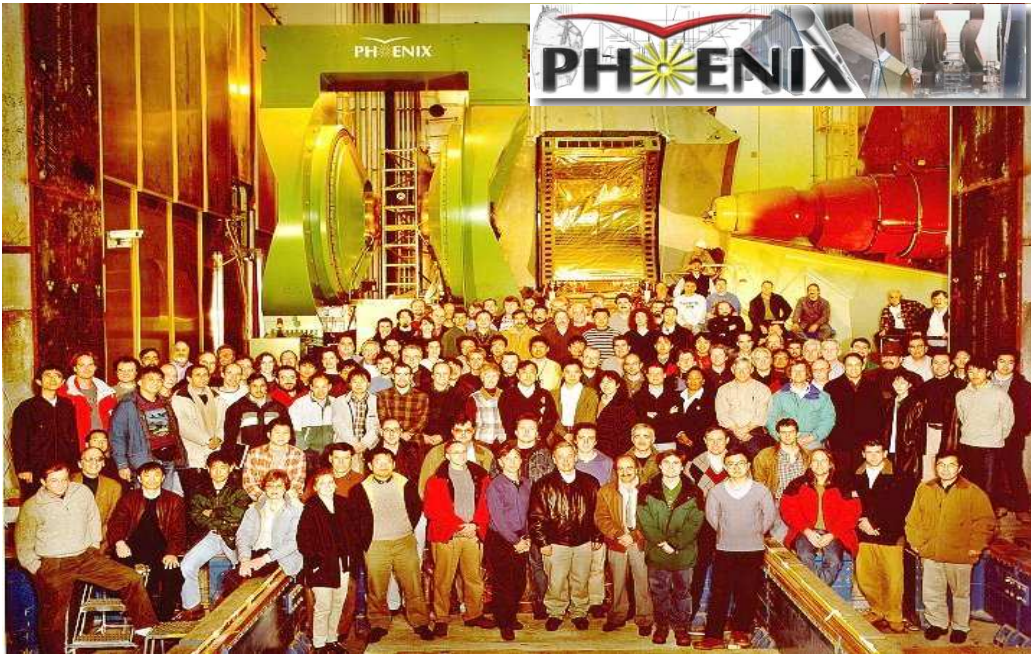
QGP Surveillance Equipment - Engineer's View



QGP Surveillance Equipment

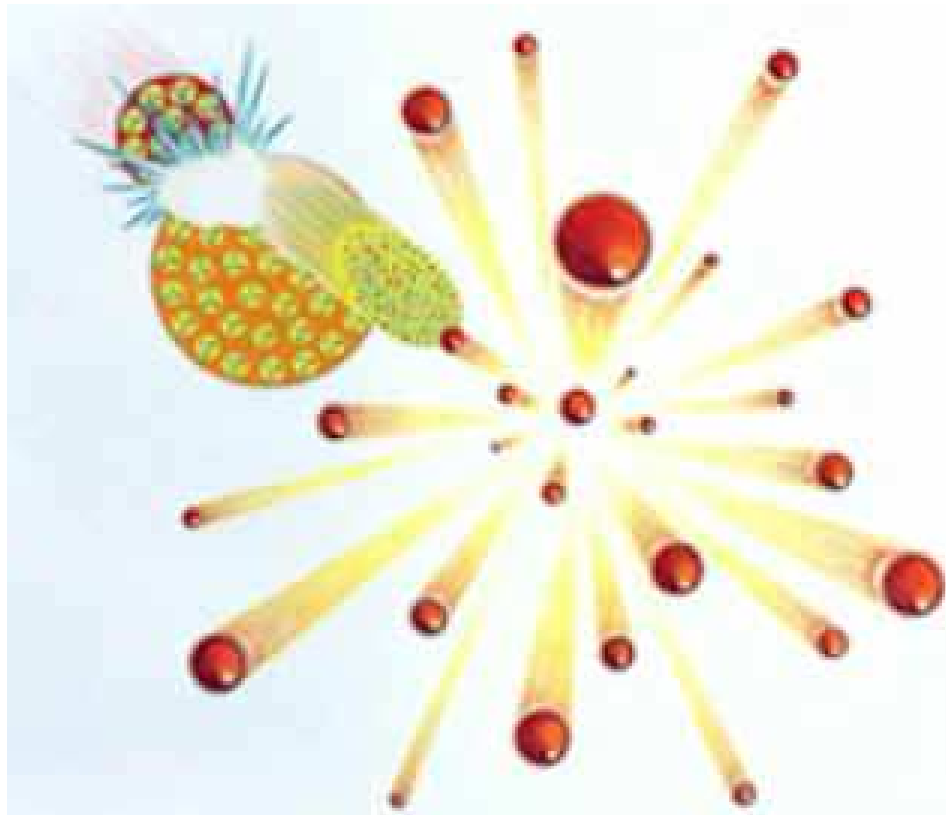


QGP Surveillance Teams



Quark & Gluon Plasma

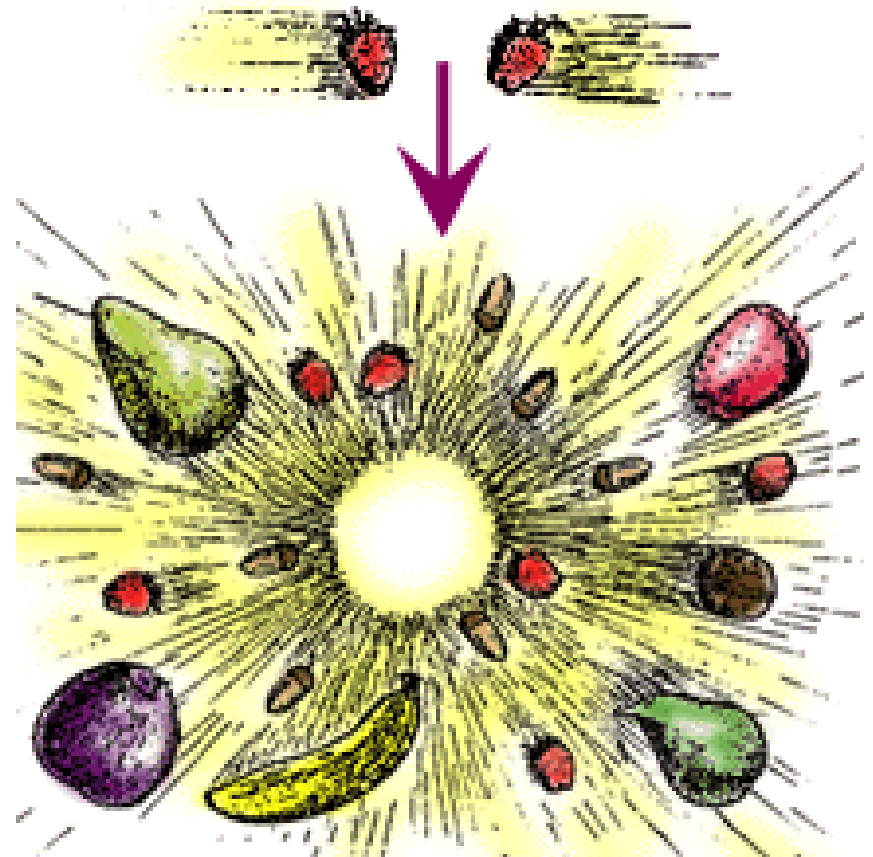
A Master of Disguise and Deception



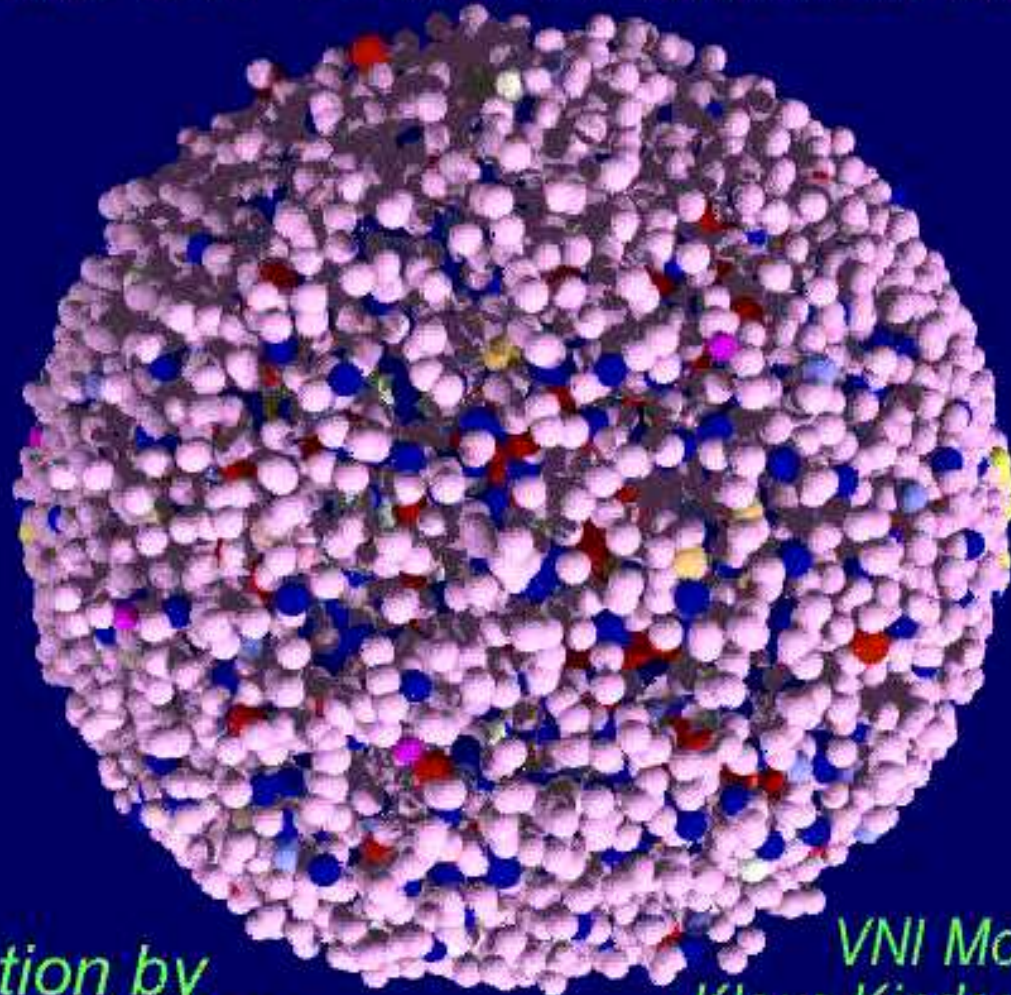
Special Relativity takes over!

$$E = mc^2$$

More than 5000 particles are
produced

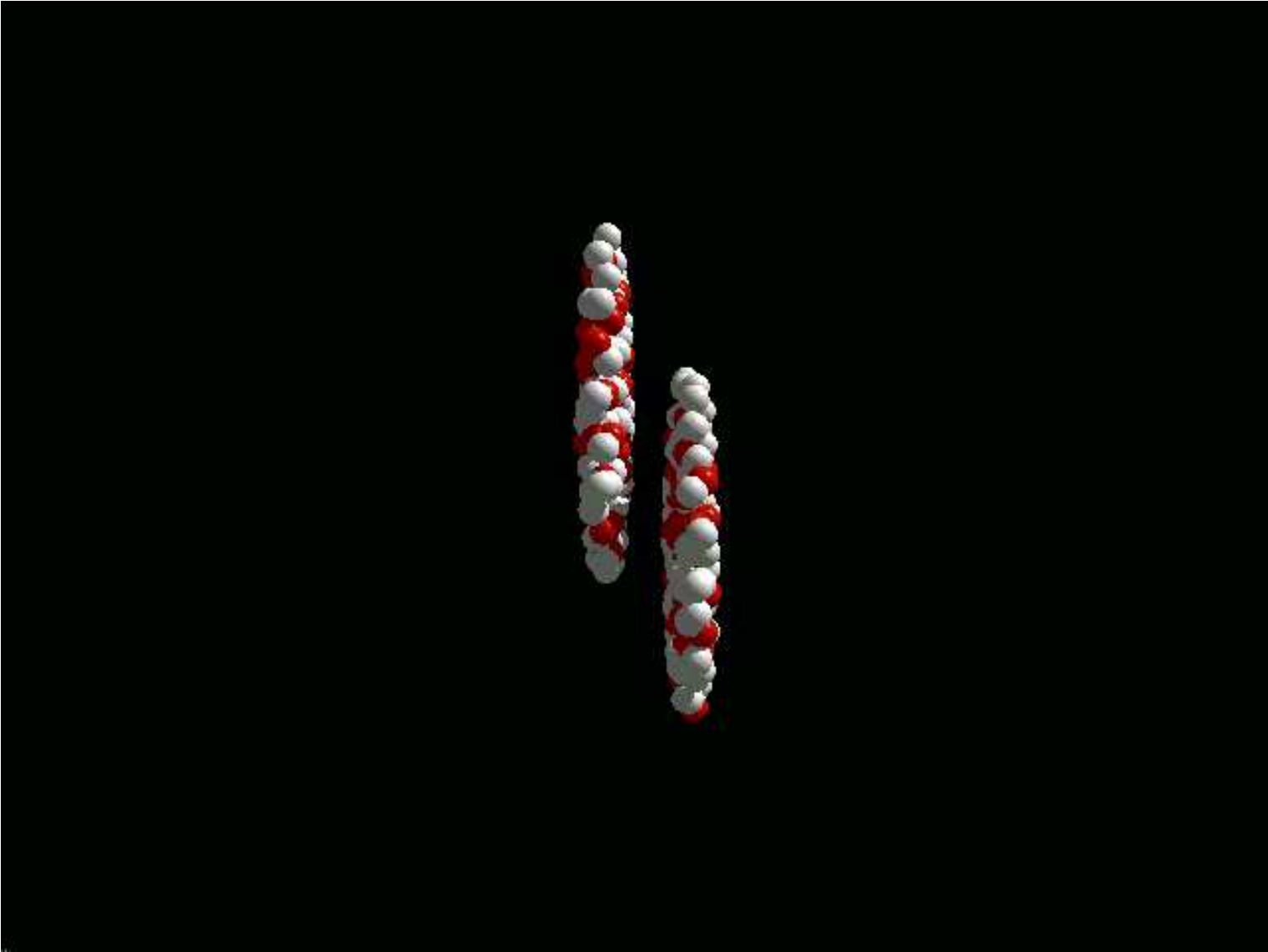


A Gold-on-Gold Collision at RHIC

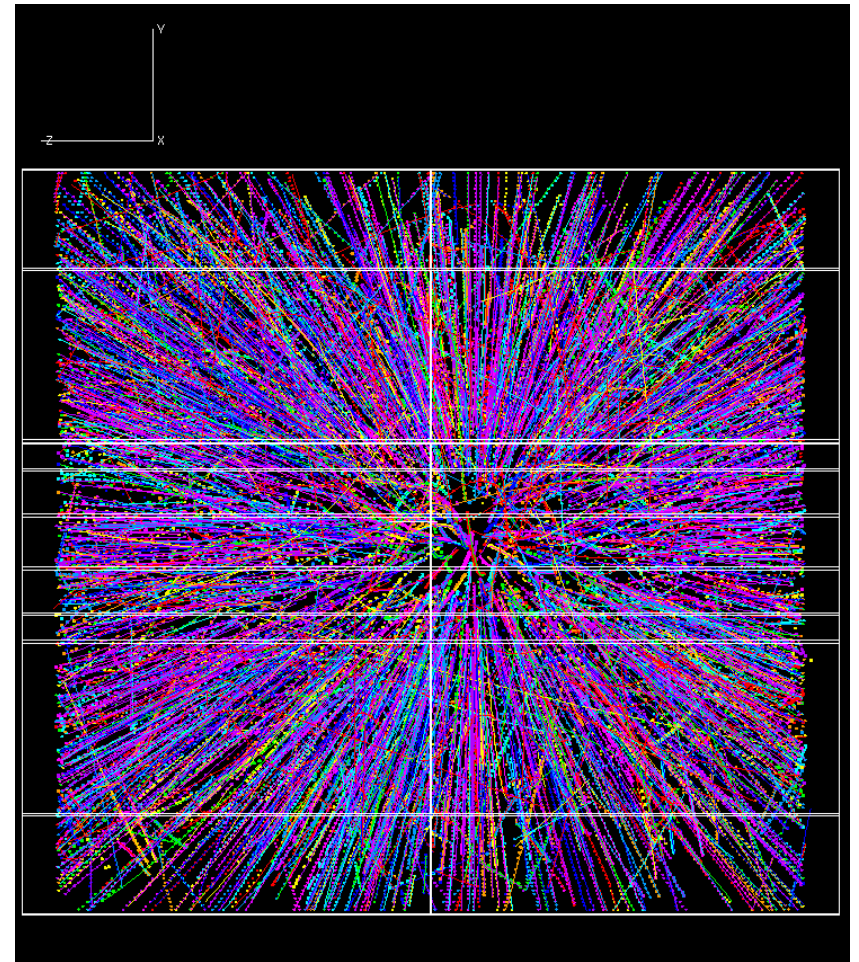
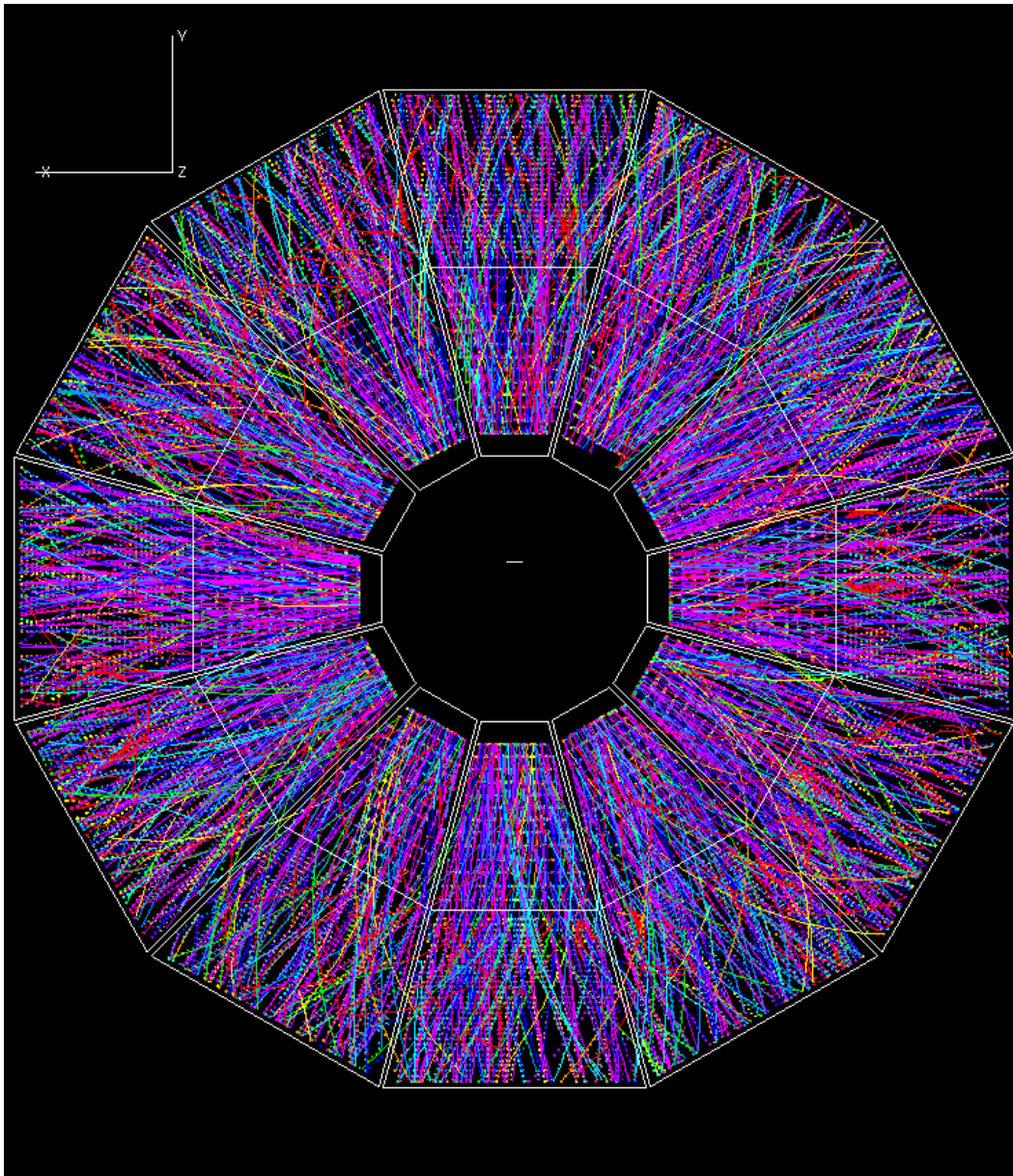


*Animation by
Jeffery T. Mitchell*

*VNI Model by
Klaus Kinder-Geiger and
Ron Longacre*

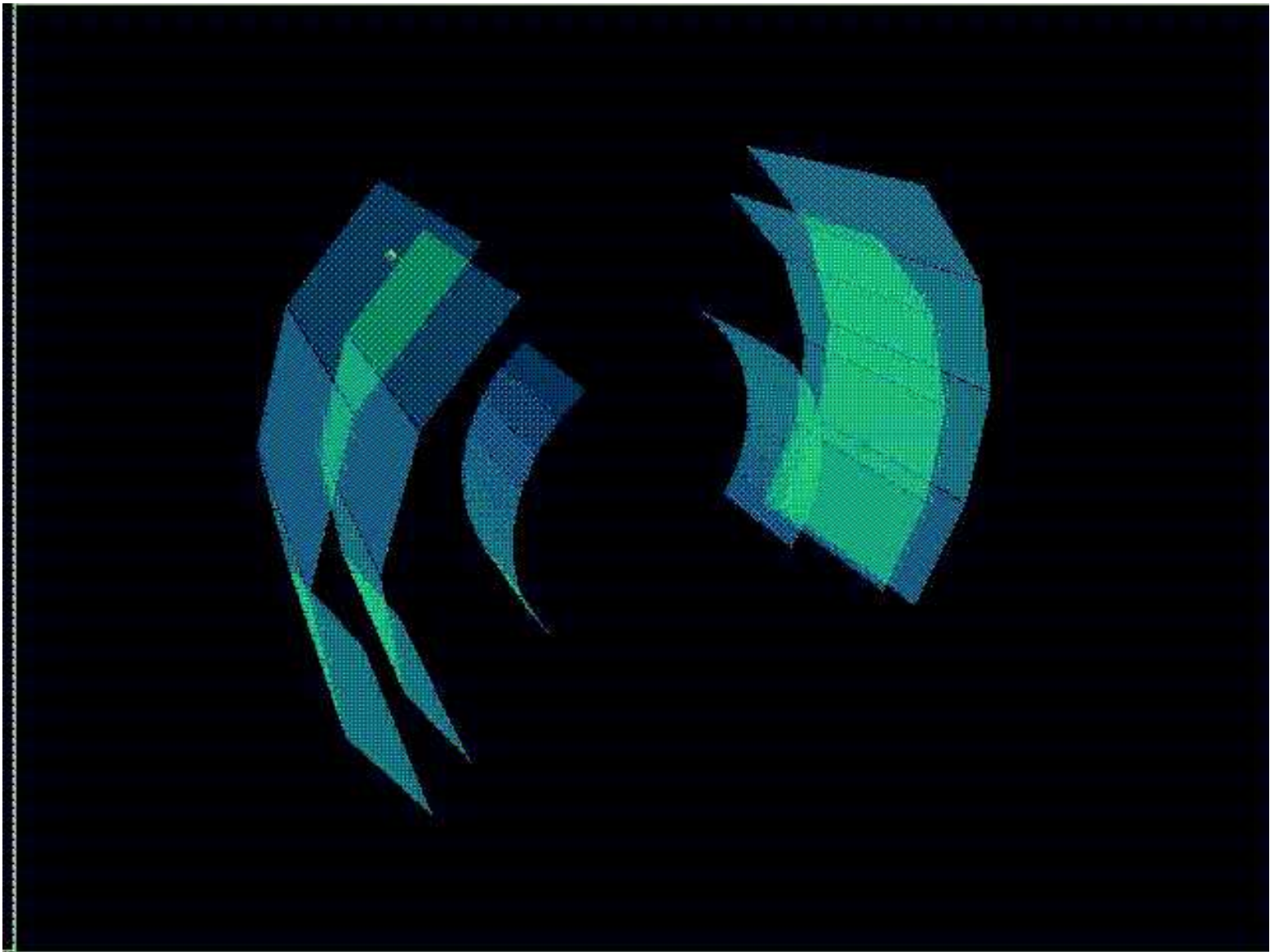


QGP Surveillance Photographs

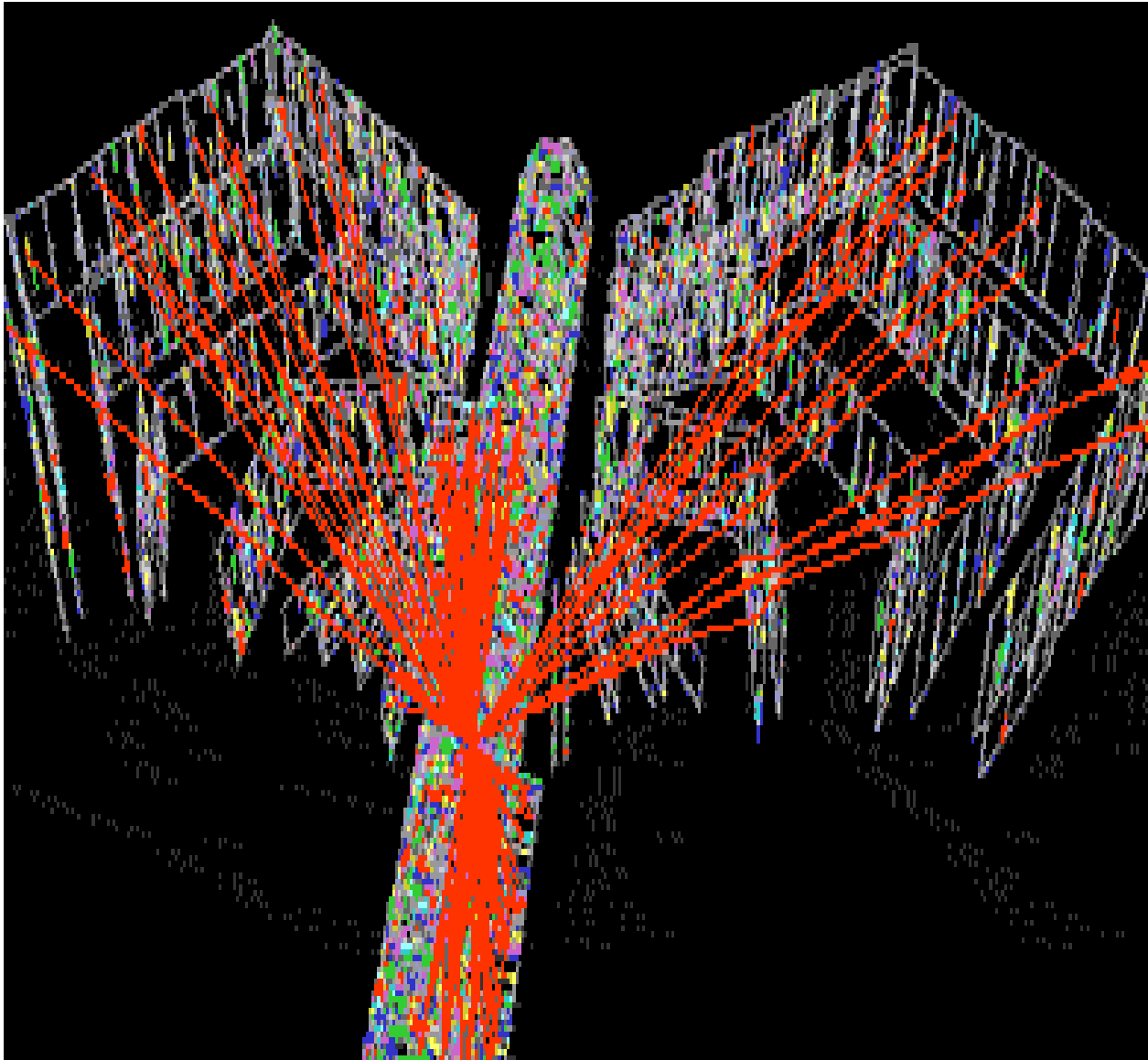


QGP Surveillance Photographs





QGP Surveillance Photographs



PHOBOS

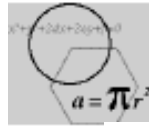
RHIC's First Results

All 4 RHIC experiments started taking data in June 2000 and ran through September 2000. A second run started concluded earlier in 2002. A third, control experiment run occurred in 2003. Millions of collisions were recorded.

Data Analysis Questions (*some of them*):

- **Hideout Characteristics:**

- Correct Shape?



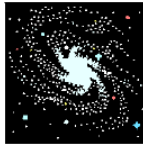
- Violent Enough?



- Hot Enough?



- Early-Universe Like?



- Fluid Enough?



- Strange Enough?



- **Have we caught a glimpse of the QGP?**

- **HOW DOES RHIC COMPARE TO PREVIOUS ATTEMPTS TO CATCH THE ELUSIVE QGP?**

Is the Hide-out the Correct Shape? Collision Geometry

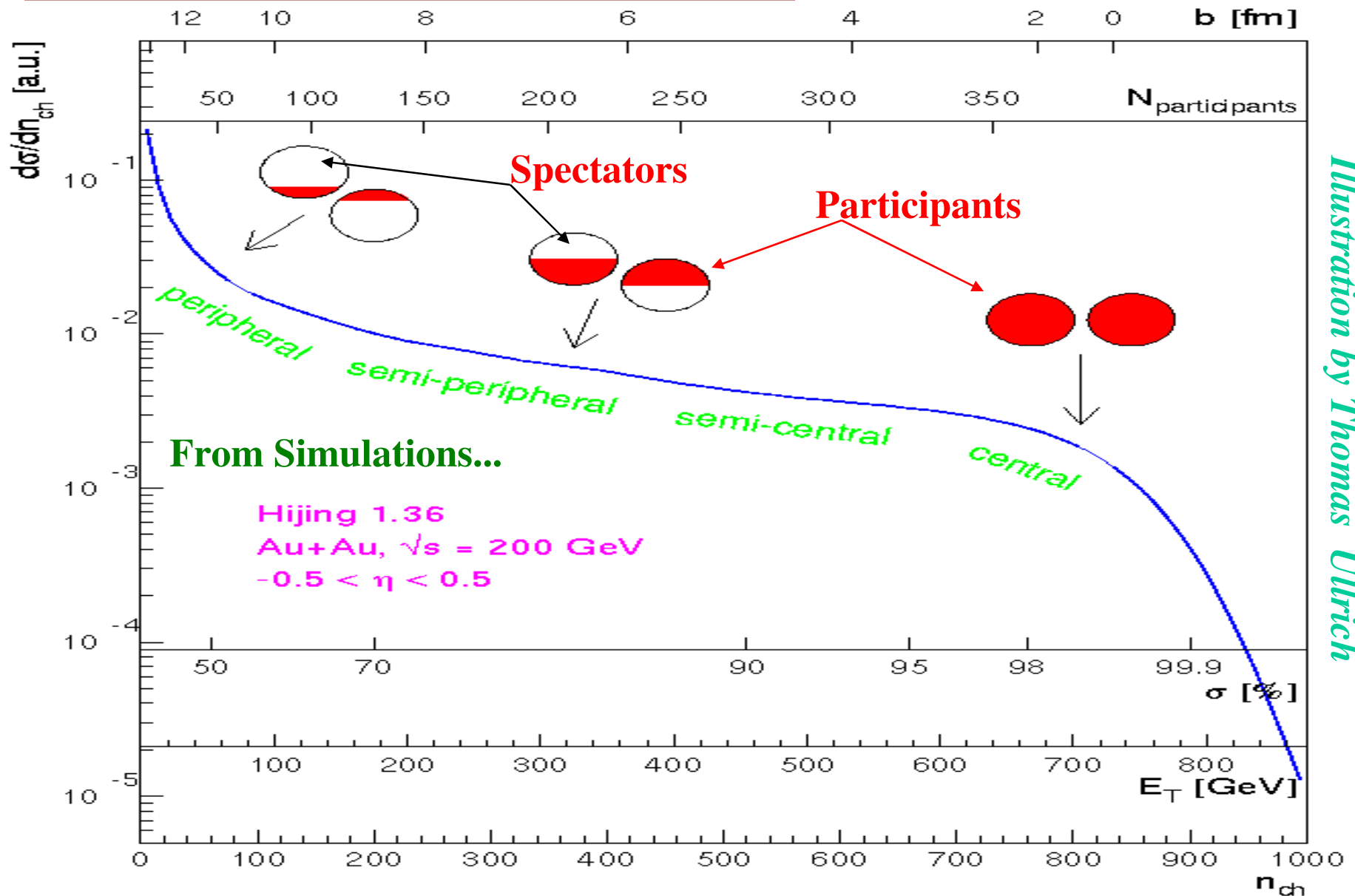
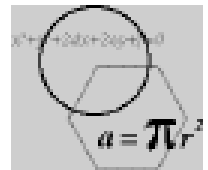
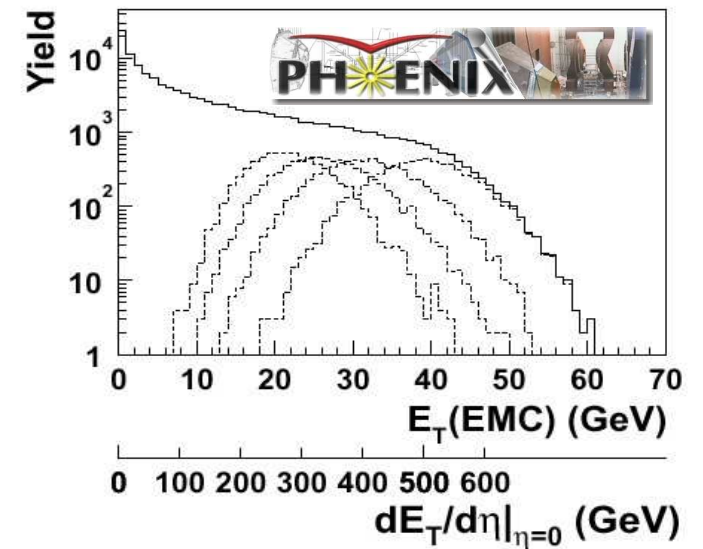
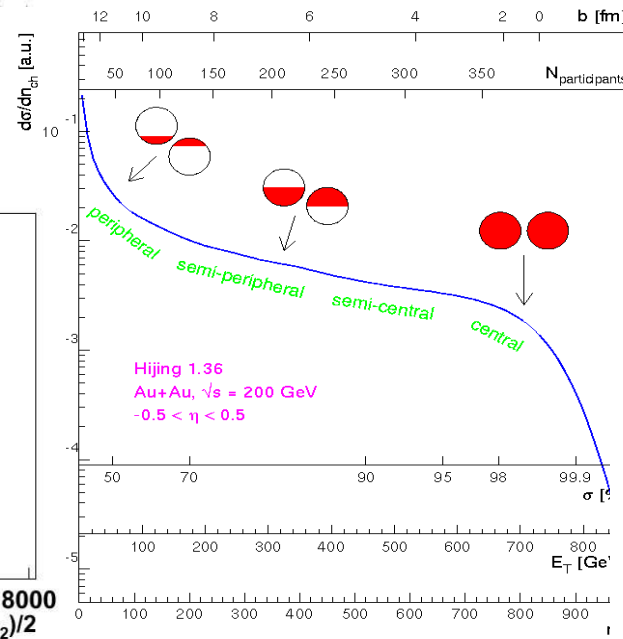
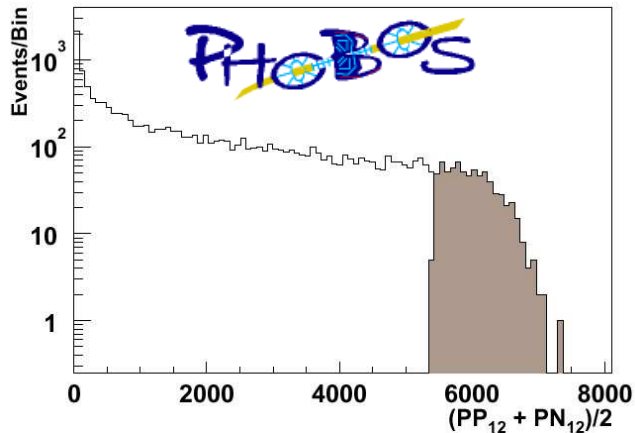
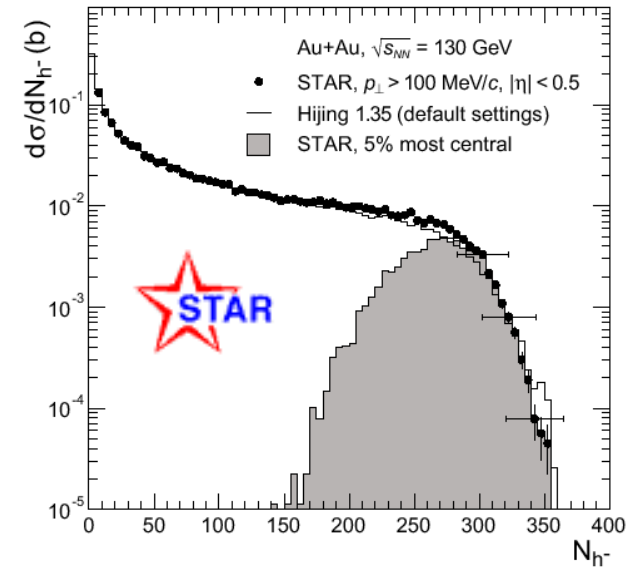
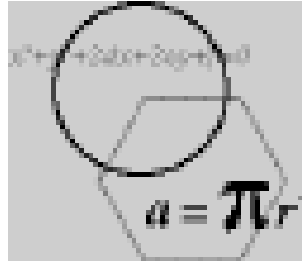
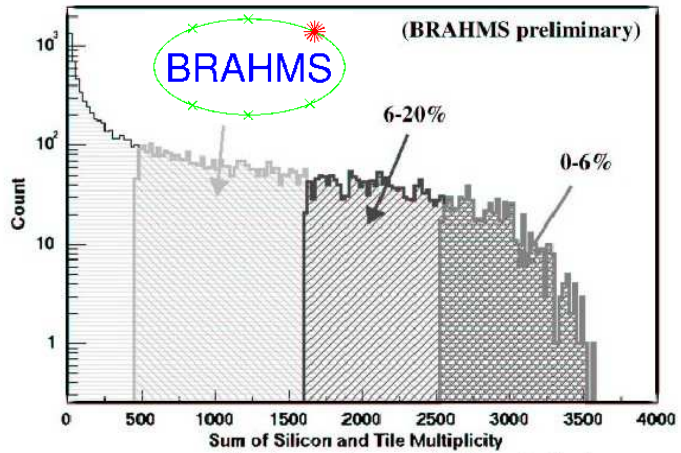
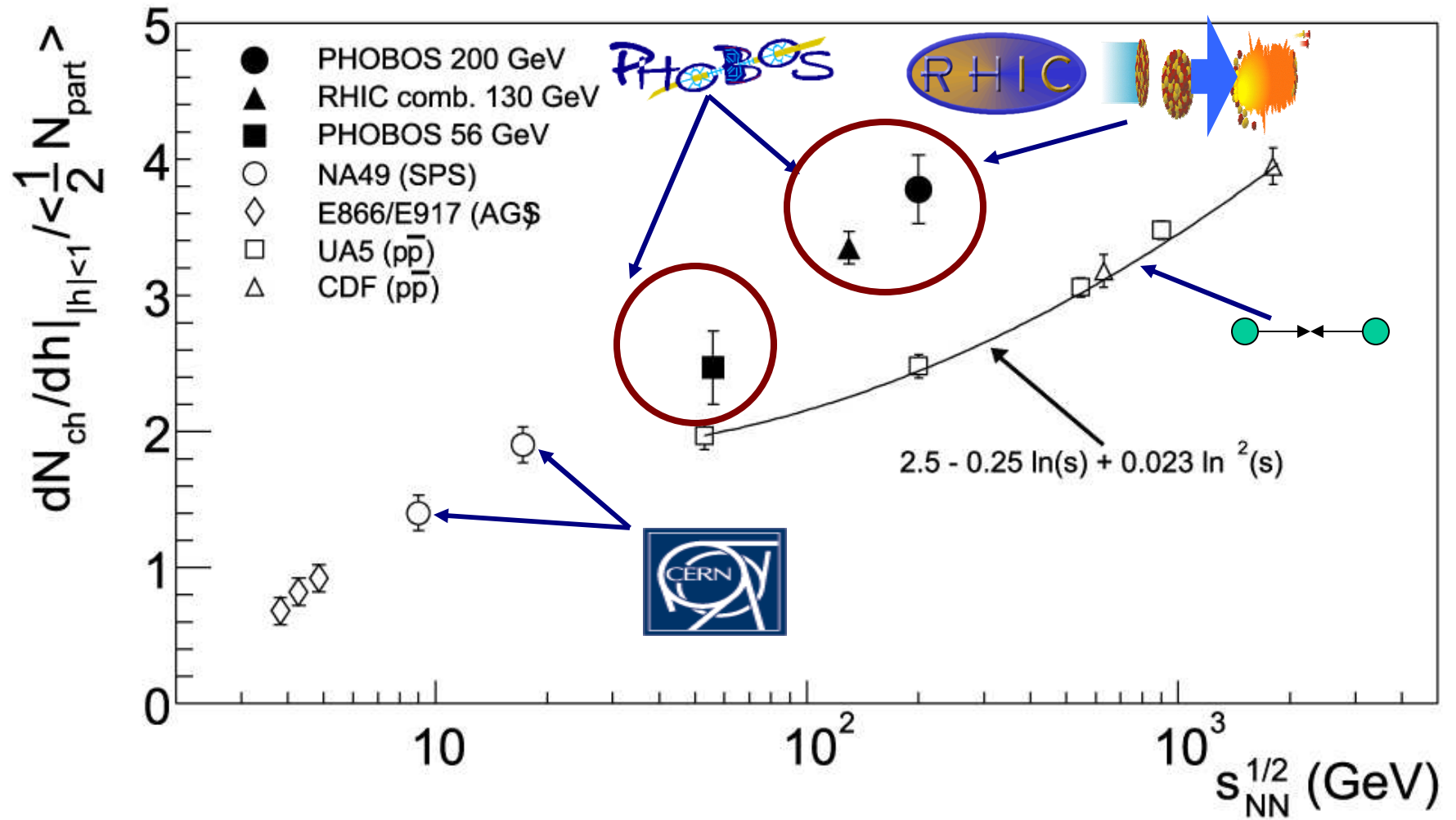


Illustration by Thomas Ulrich

Is the hide-out the correct shape? **Yes!**

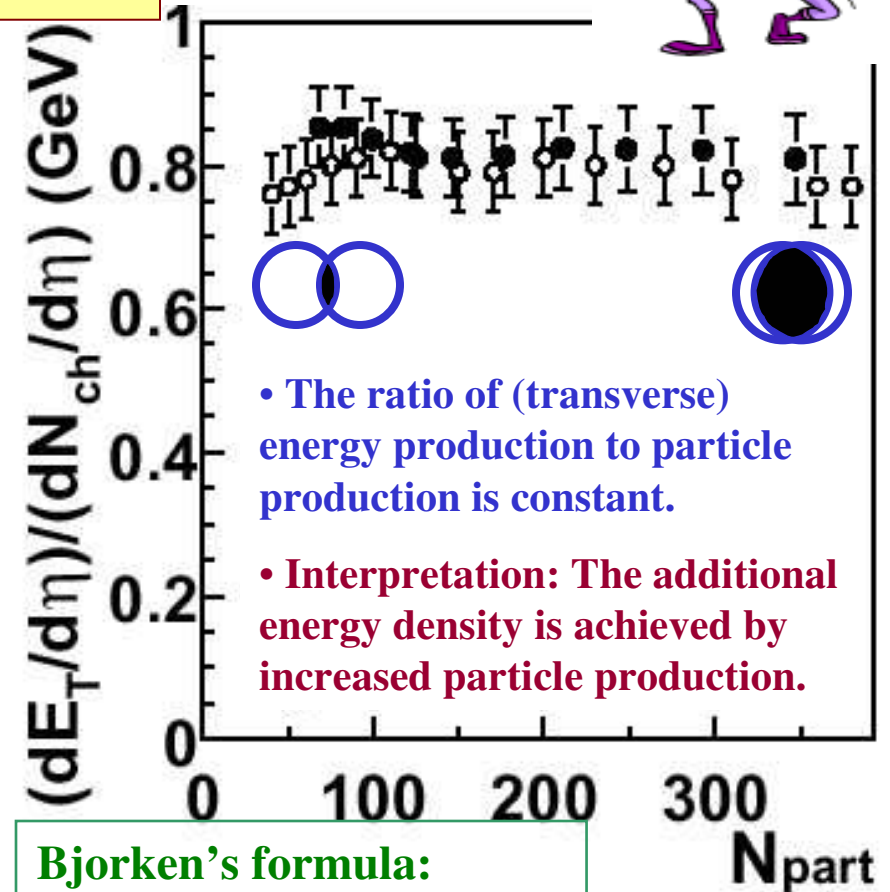
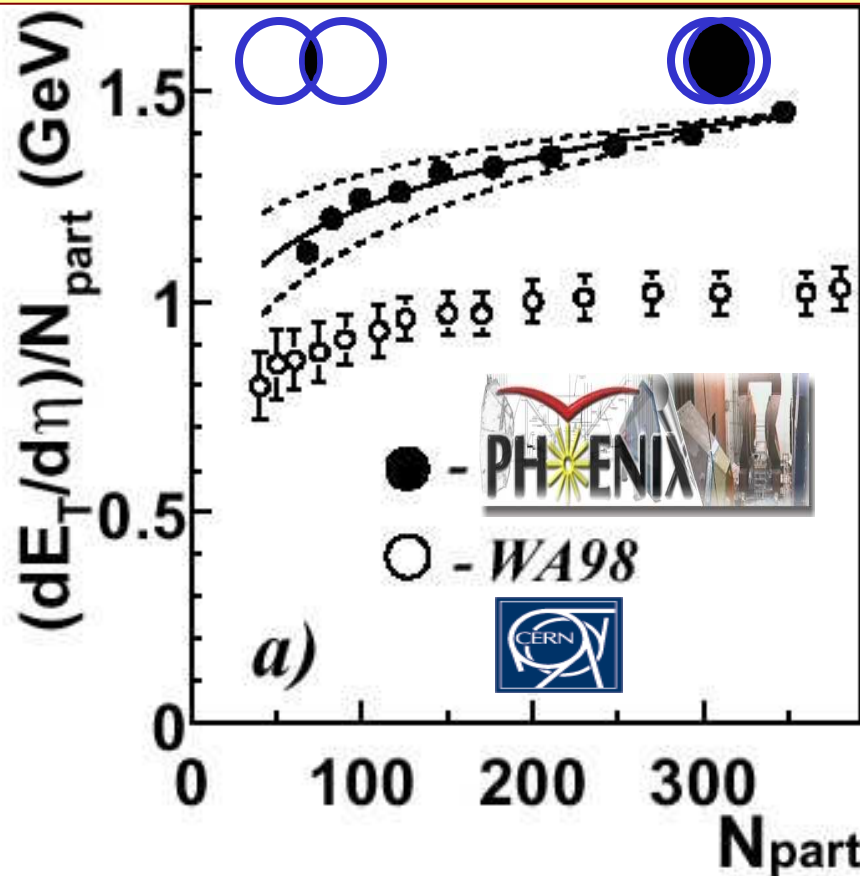


Is the Hide-out Violent Enough? Particle Production



Is the Hide-out Violent Enough?

Energy Density



- Energy density = Energy per unit volume

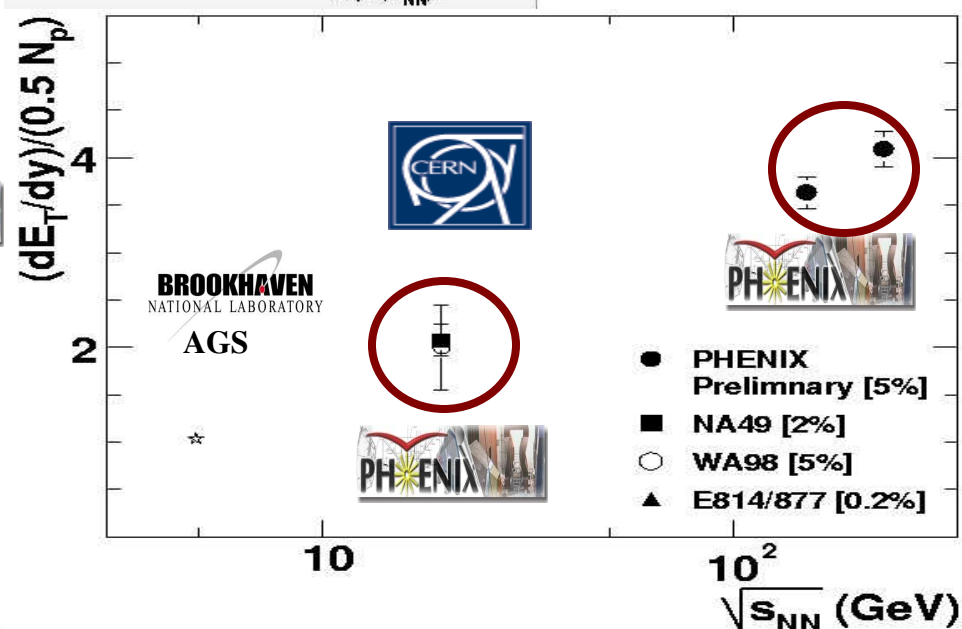
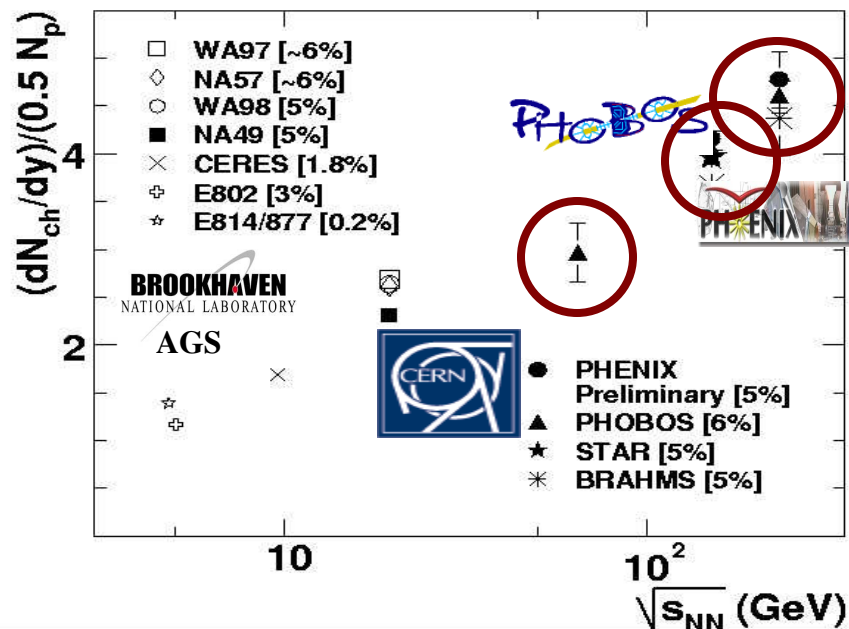
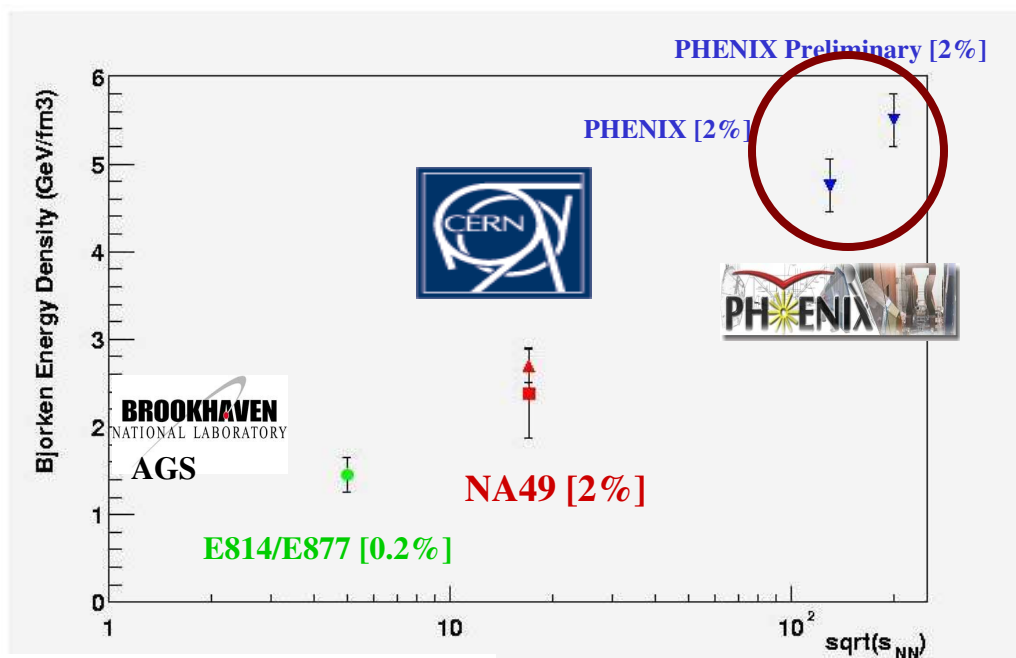
Bjorken's formula:
initial energy density
 $\langle \epsilon_0 \rangle \sim 1/\pi R^2 \tau_0 dE_t/dy$

- At CERN, the energy density produced is about 2.9 GeV/fm³, or 18X normal nuclear matter!
- At RHIC, the energy density produced is about 5.3 GeV/fm³, or 33X normal nuclear matter!

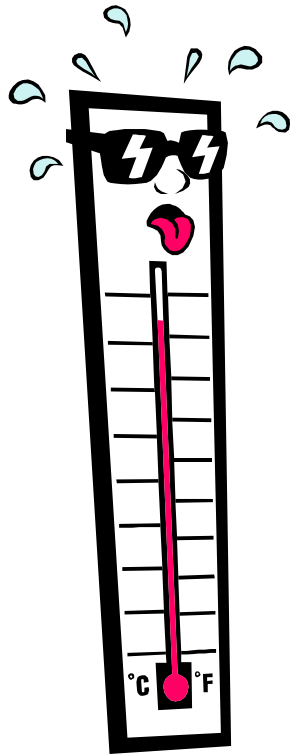
Is the RHIC hide-out more violent than previous hide-outs?



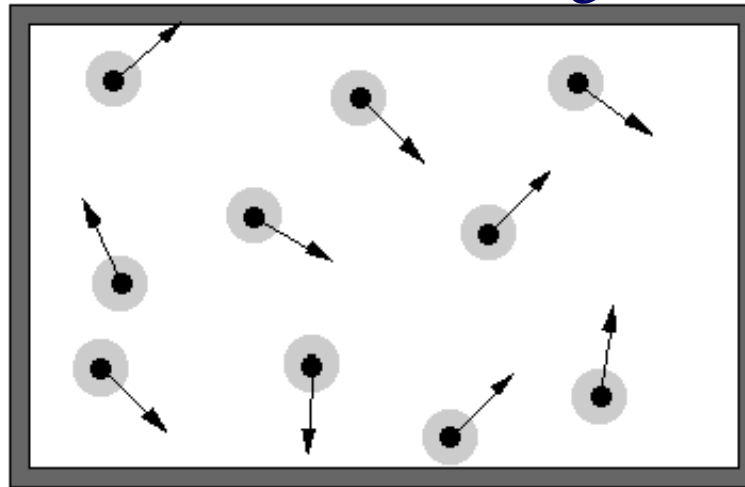
Yes!



Is the hide-out hot enough? - Let's make a thermometer!



Let's assume that the center of the collision acts like a gas...



If the system is thermalized, the velocity distribution of the molecules is described by a Maxwell-Boltzmann distribution:

$$f(v)dv = 4\pi \left(\frac{m}{2k_B T} \right)^{3/2} v^2 \exp\left(-\frac{mv^2}{2k_B T} \right) dv$$

Temperature



Is the hide-out hot enough? - Let's make a thermometer!

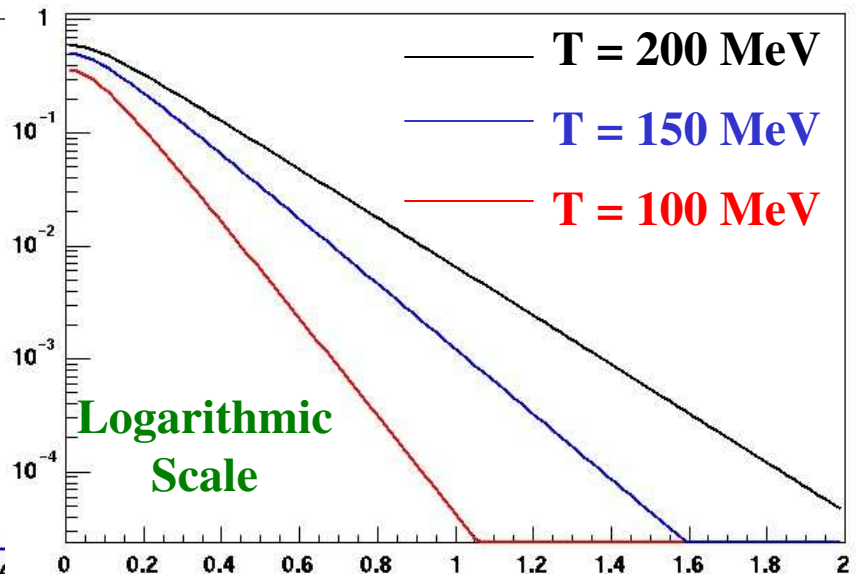
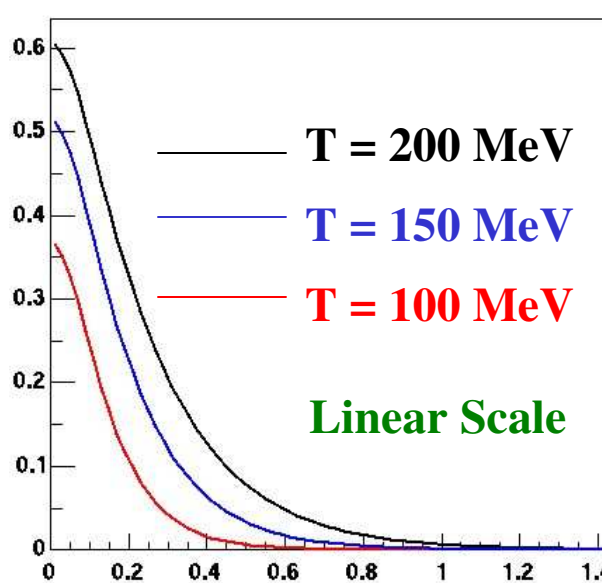
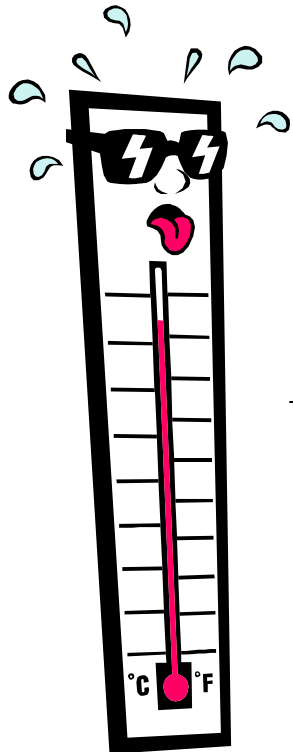
To *simplify* the data analysis, modify the Maxwell-Boltzmann equation to be expressed in a variable called transverse mass.

$$m_t = \sqrt{m_0^2 + p_t^2}$$

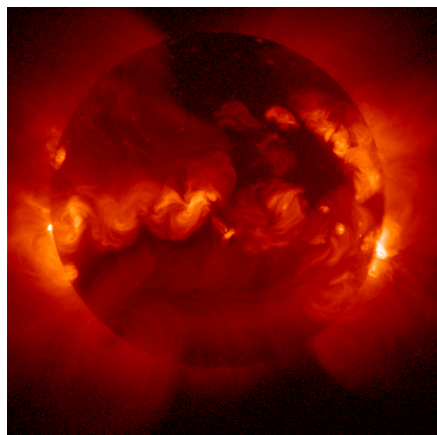
$$\frac{1}{p_t} \frac{dN}{dp_t} = \frac{1}{m_t} \frac{dN}{dm_t}$$

The distribution becomes exponential in the transverse mass.

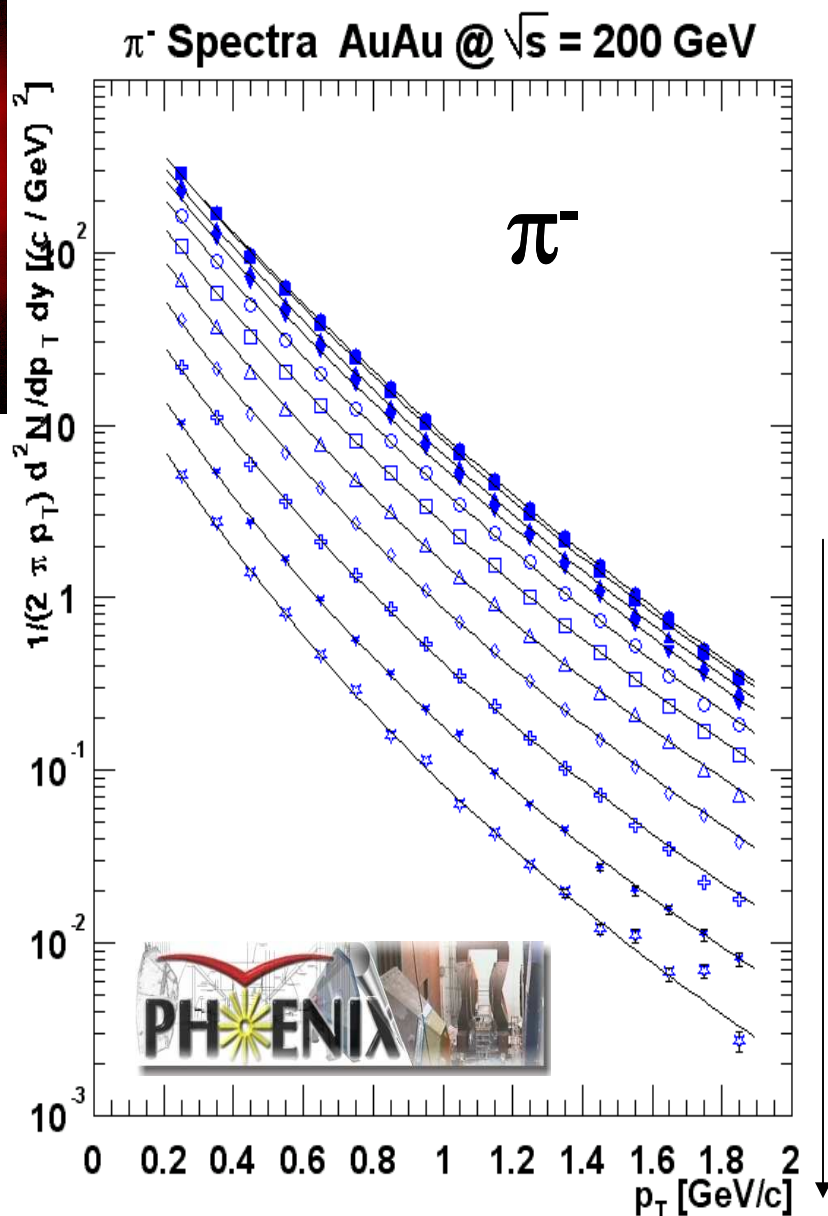
$$\frac{1}{m_t} \frac{dN}{dm_t} \propto e^{-\frac{m_t}{T}}$$



Is the hide-out hot enough? - Transverse Momentum Spectra

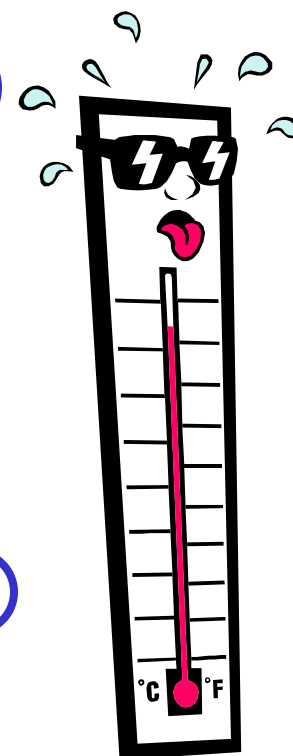


The hideout is
100,000 times
the
temperature at
the center of
the sun!

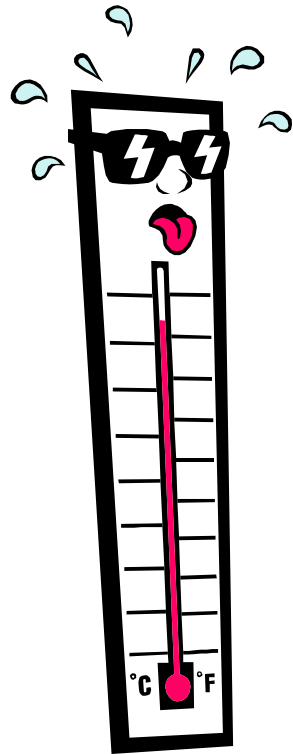


centrality

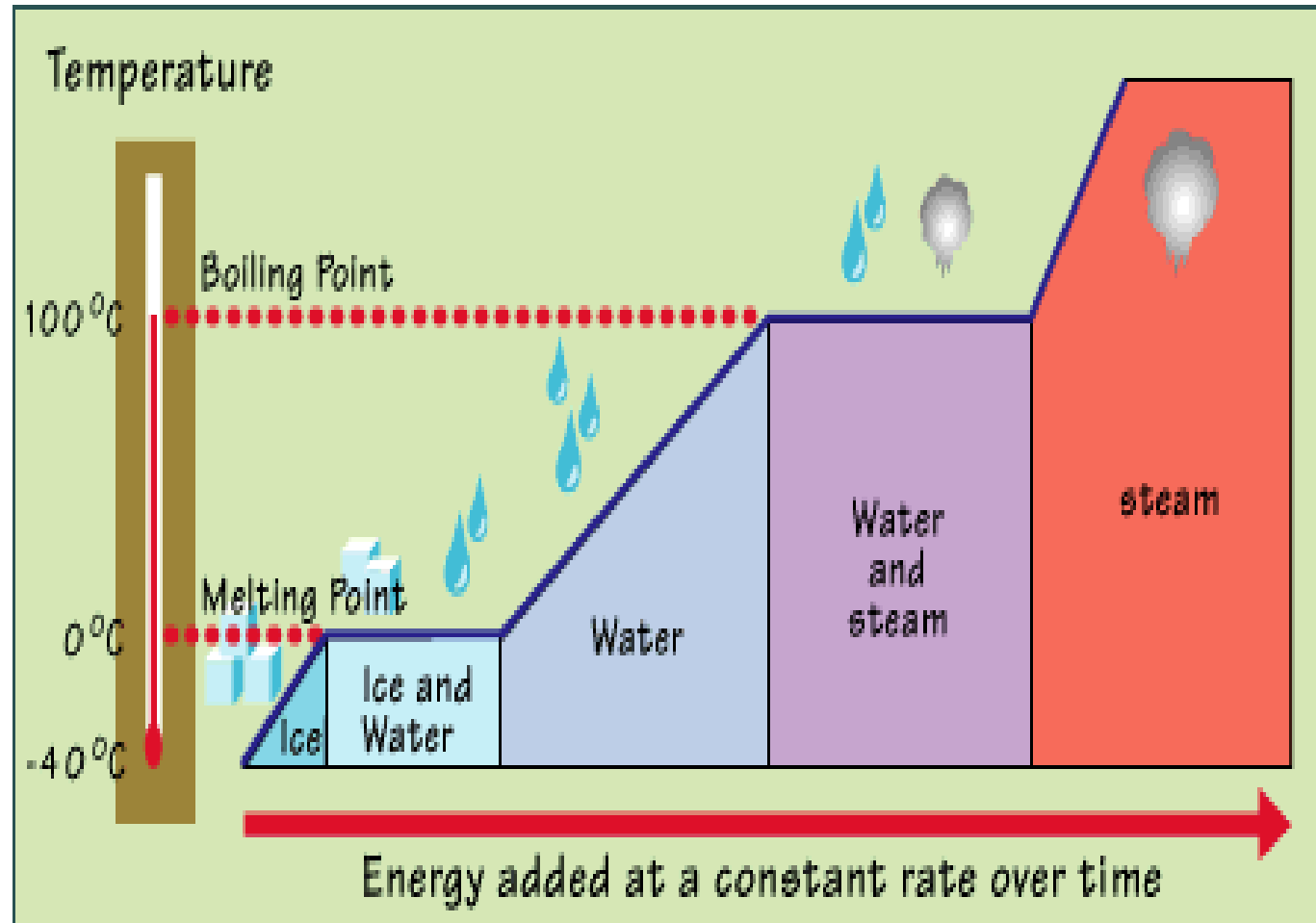
- 0 - 5 %
- 5 - 10 %
- 10 - 15 %
- 15 - 20 %
- 20 - 30 %
- 30 - 40 %
- 40 - 50 %
- 50 - 60 %
- 60 - 70 %
- 70 - 80 %
- 80 - 91 %



Is the hide-out hot enough? - Temperature in a Phase Transition



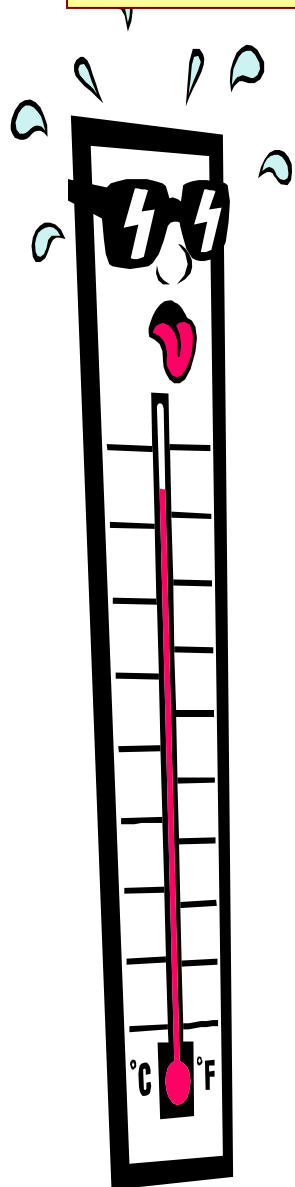
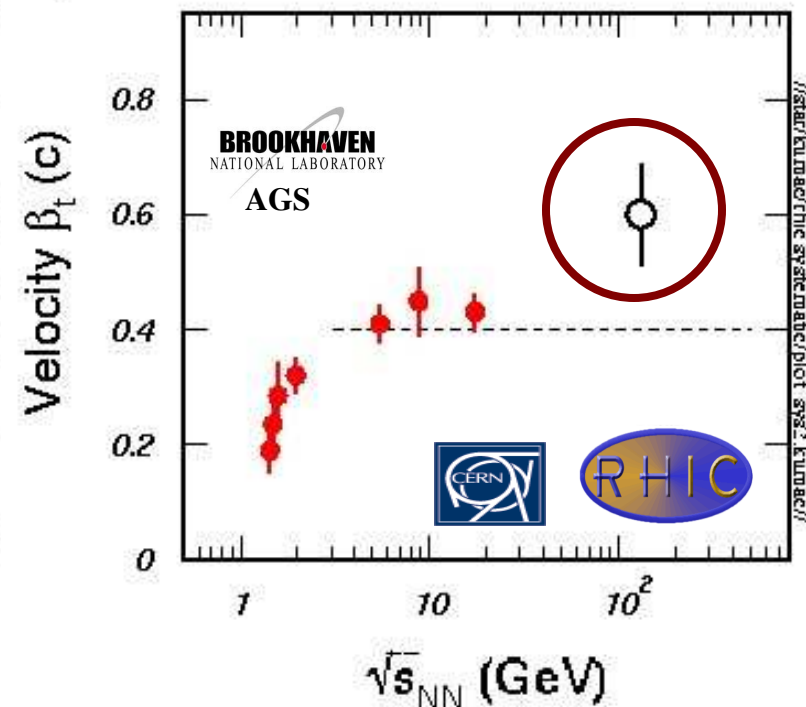
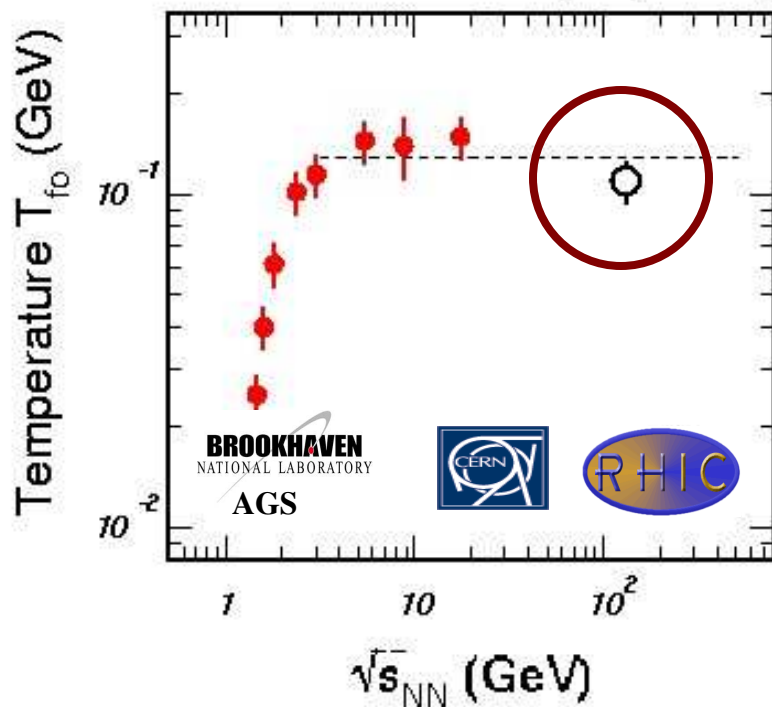
Heating Curve for Water



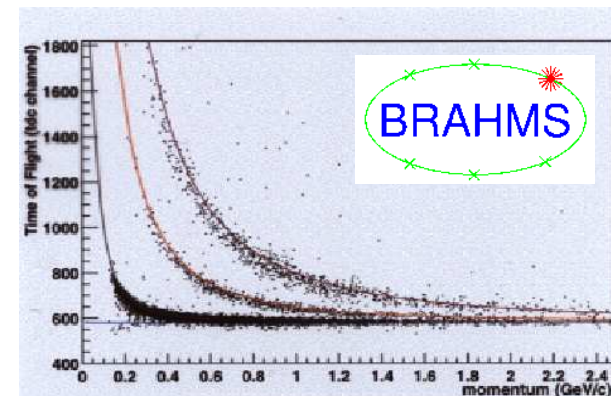
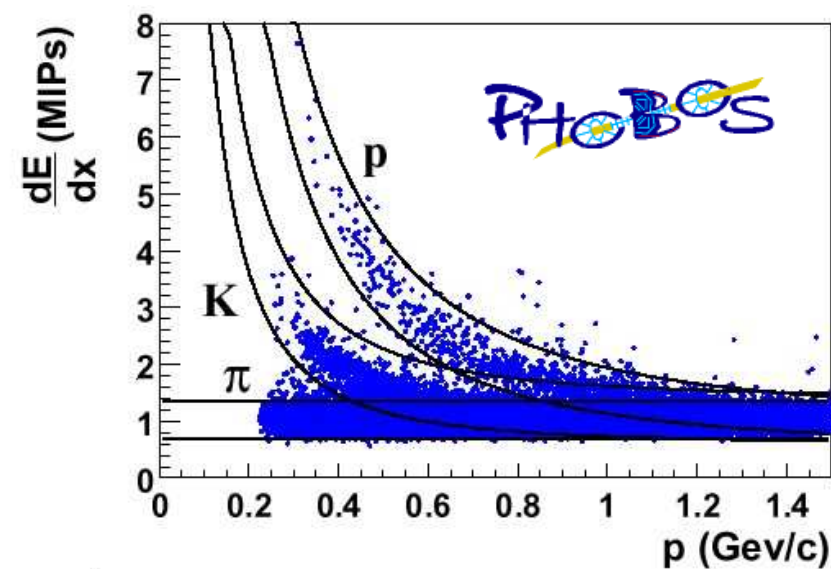
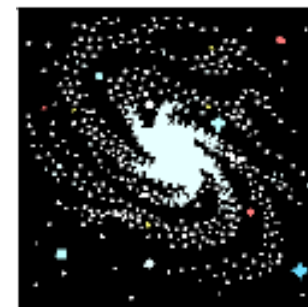
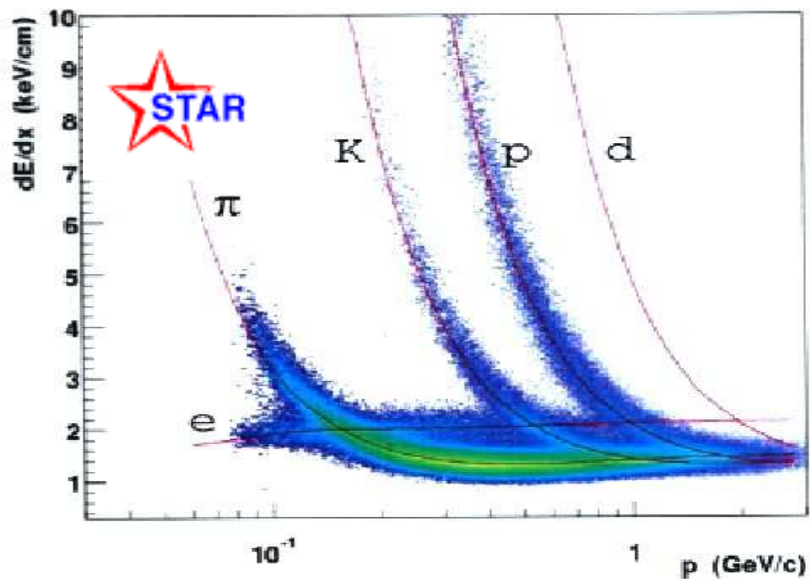
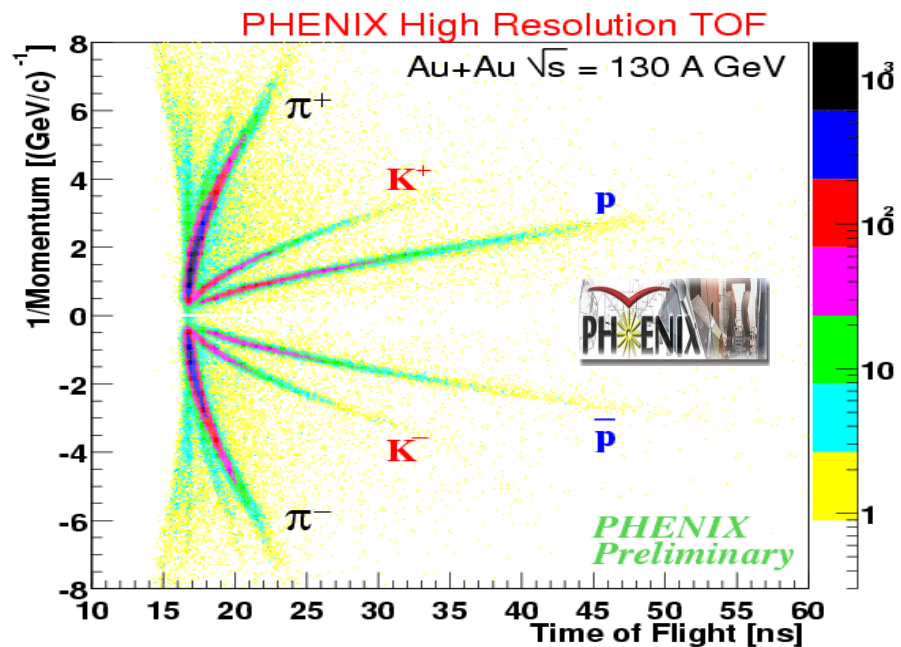
Is the RHIC hide-out hotter than previous hideouts?

Compiled by
Nu Xu

Au(Pb) + Au(Pb) Central Collisions

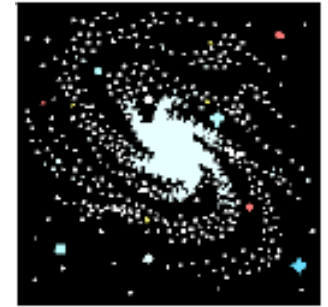


Particle Recognition



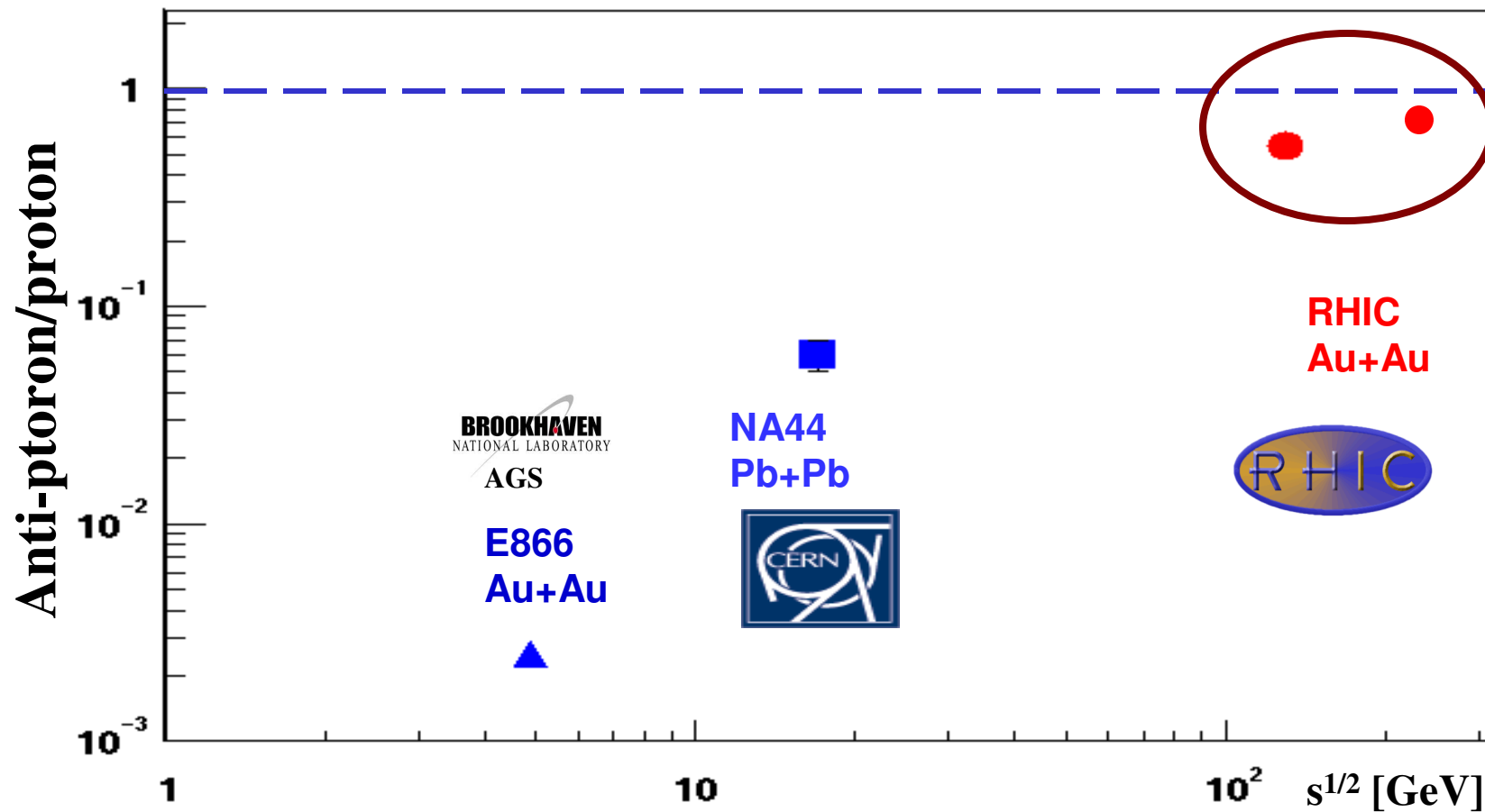
Is the hide-out disguised as the early universe?

Almost...

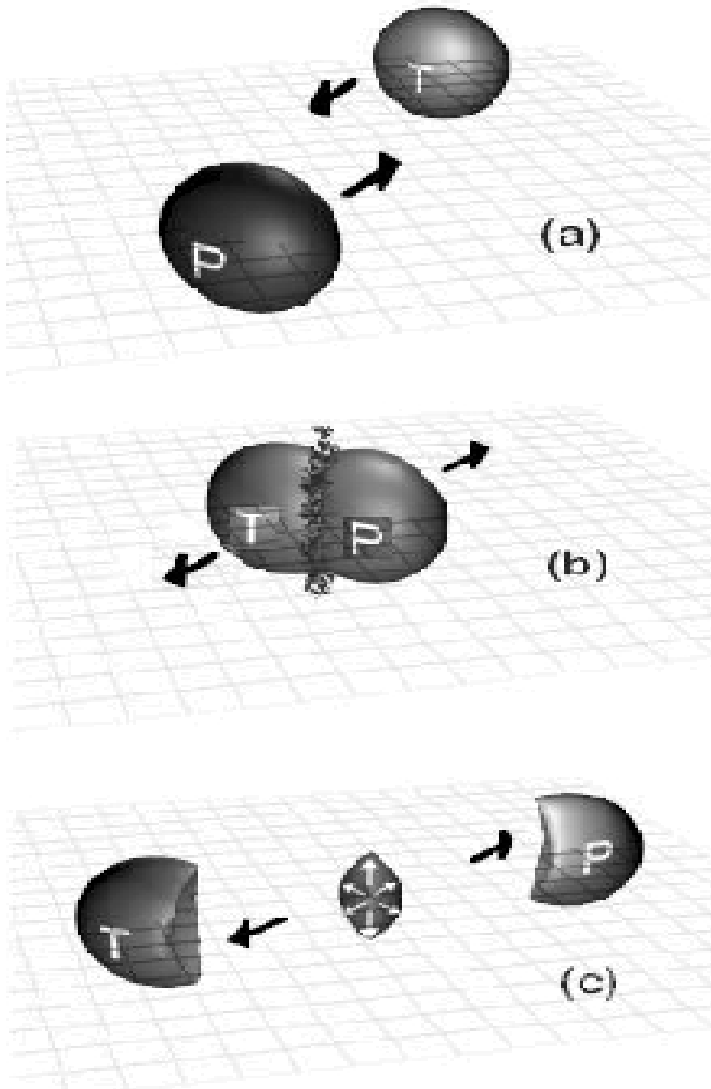


In the Early Universe, the

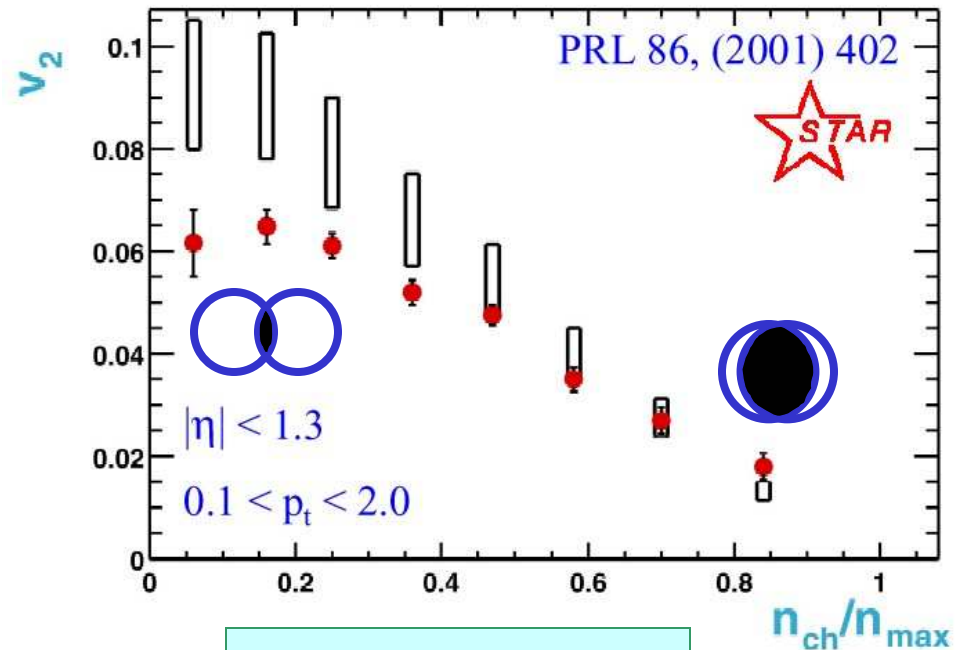
Anti-proton/proton = 0.999999999



Does the RHIC hide-out “go with the flow”?



$$V_2 = \langle (p_x^2 - p_y^2) / (p_x^2 + p_y^2) \rangle$$

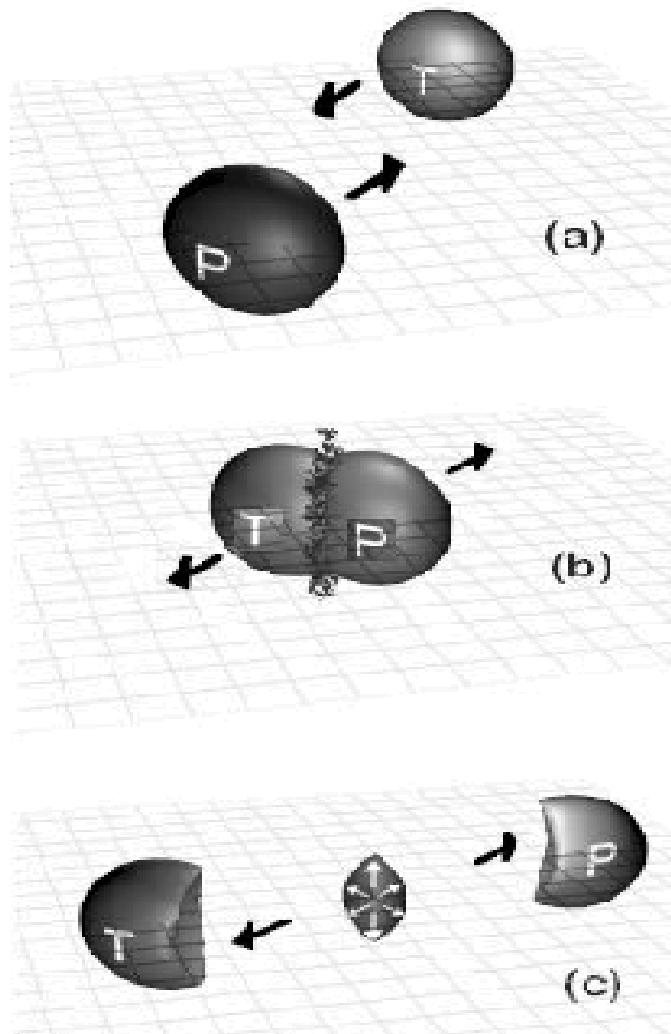


Interpretation:
Consistent with
significant
thermalization.
No unusual
structure that
could be from a
phase transition.

Does the RHIC hide-out “go with the flow”
more than previous hide-outs?

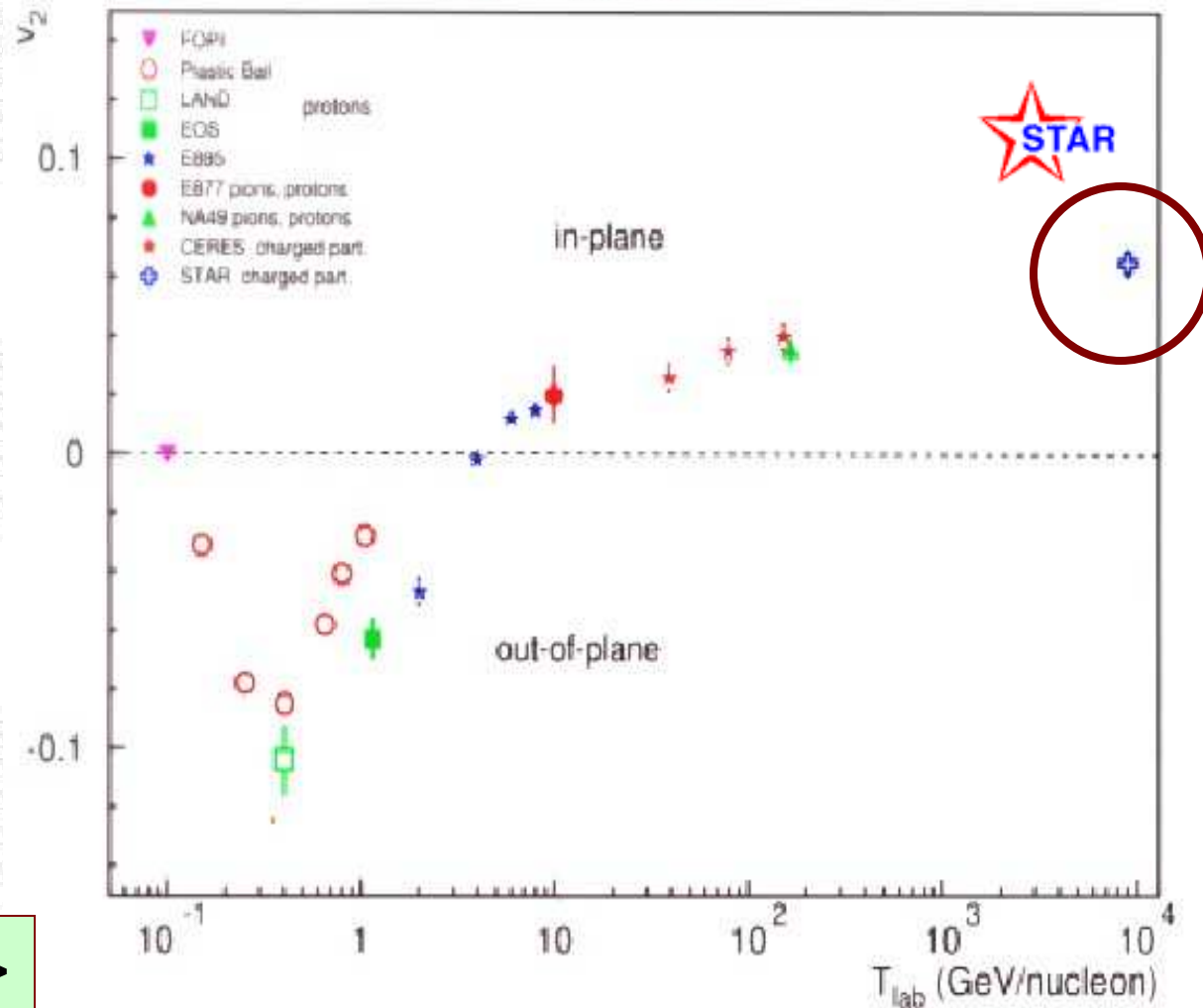


Yes!



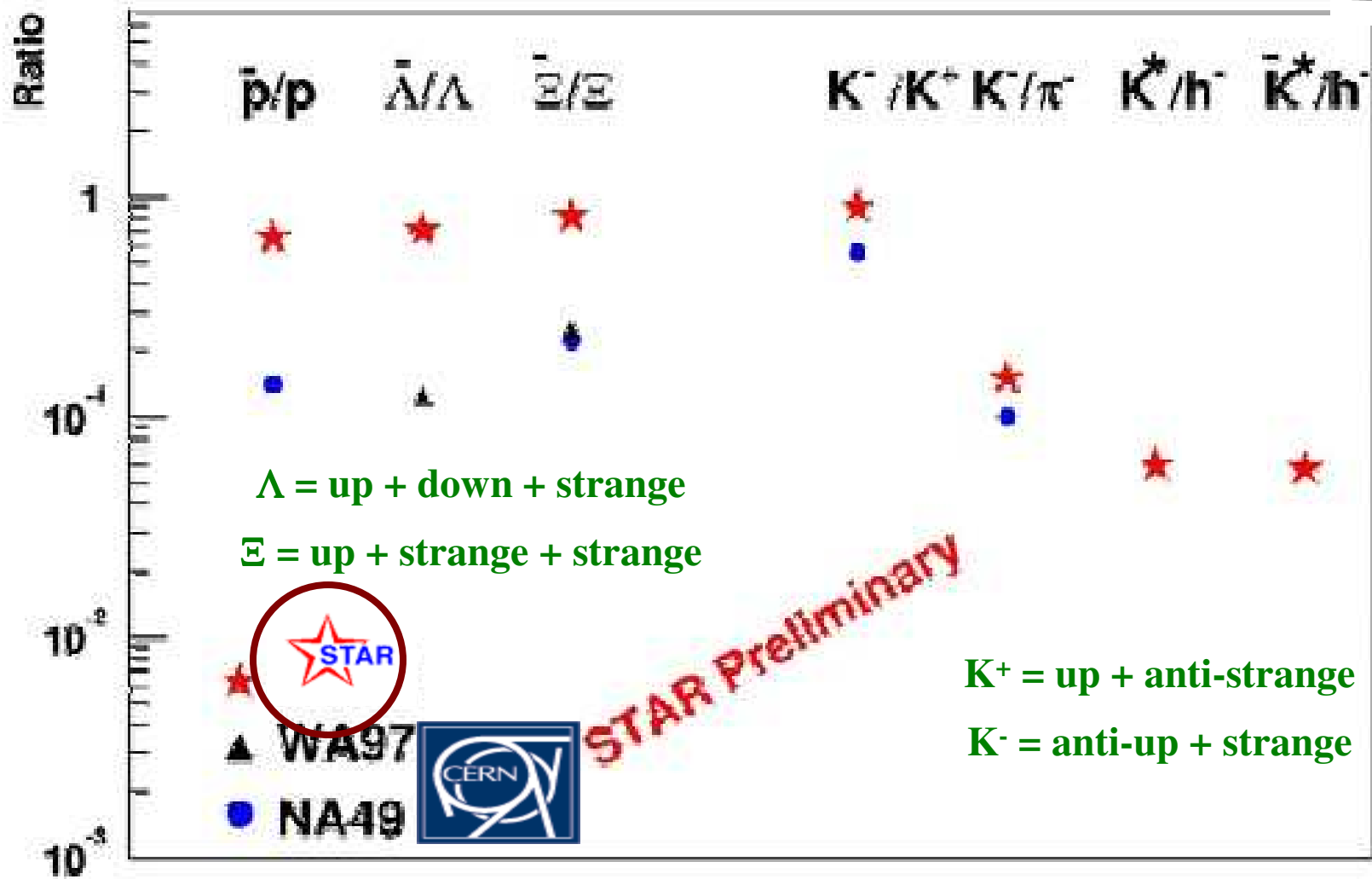
$$V_2 = \langle (p_x^2 - p_y^2) / (p_x^2 + p_y^2) \rangle$$

elliptic flow in Au+Au collisions

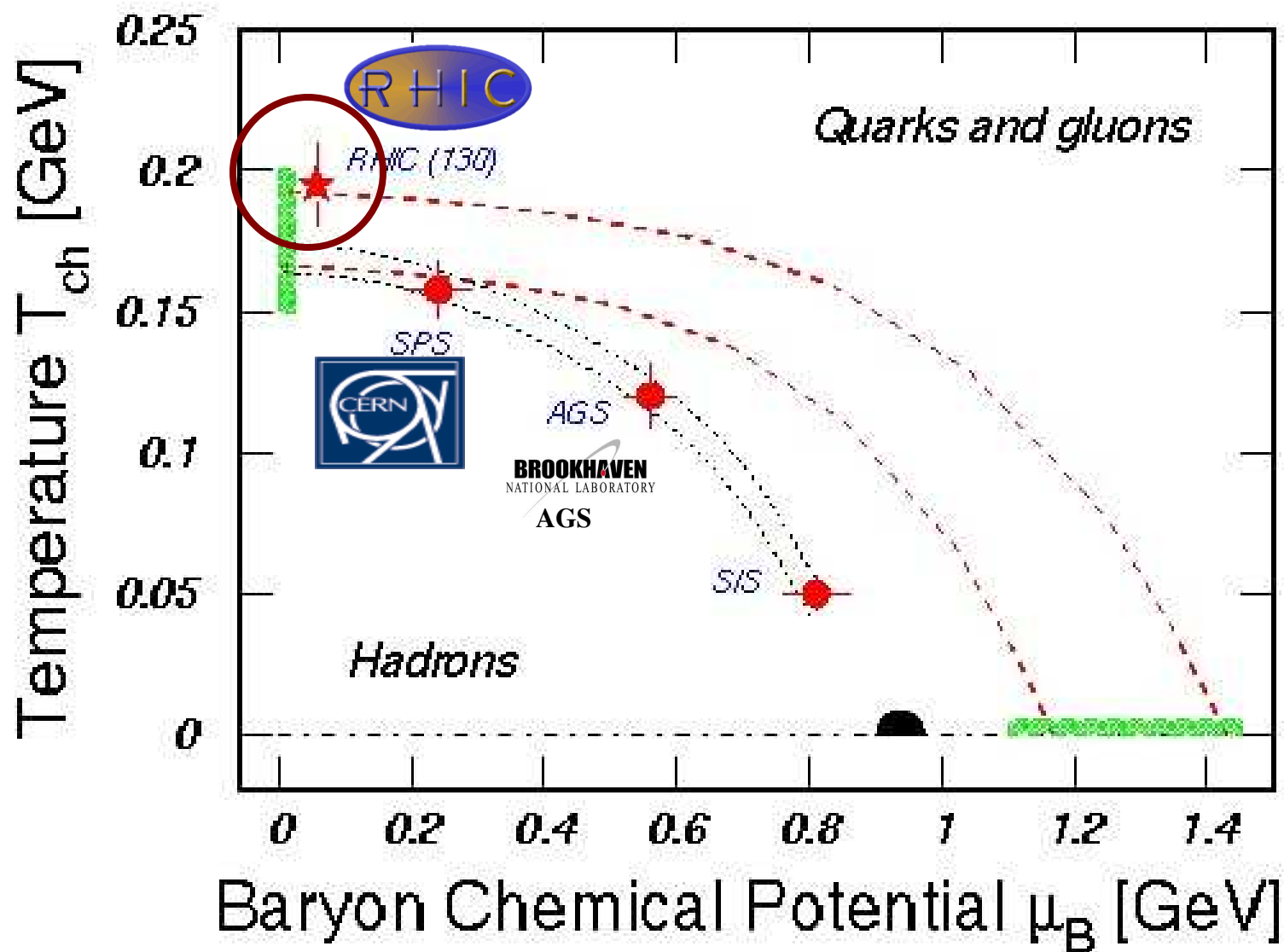


Is the RHIC Hide-out Stranger then
previous hide-outs?

Yes!



Speculation about the status of the hide-out



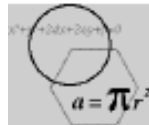
RHIC's First Results: Review So Far

Data Analysis Questions (*some of them*):

• Hideout Characteristics:



• Correct Shape?



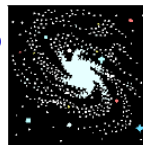
• Violent Enough?



• Hot Enough?



• Early-Universe Like?



• Fluid Enough?



• Strange Enough?



• Have we caught a glimpse of the QGP?



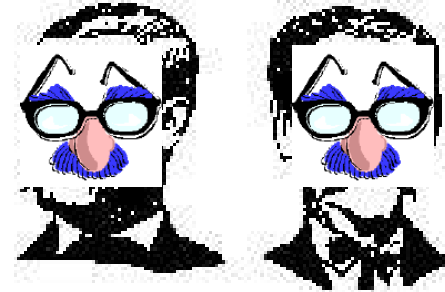
• HOW DOES RHIC COMPARE TO PREVIOUS ATTEMPTS TO CATCH THE ELUSIVE QGP?

More violent, just as hot, more like the early universe, more fluid, and stranger!

Quark & Gluon Plasma

A Master of Disguise and Deception

Can we penetrate the disguise?

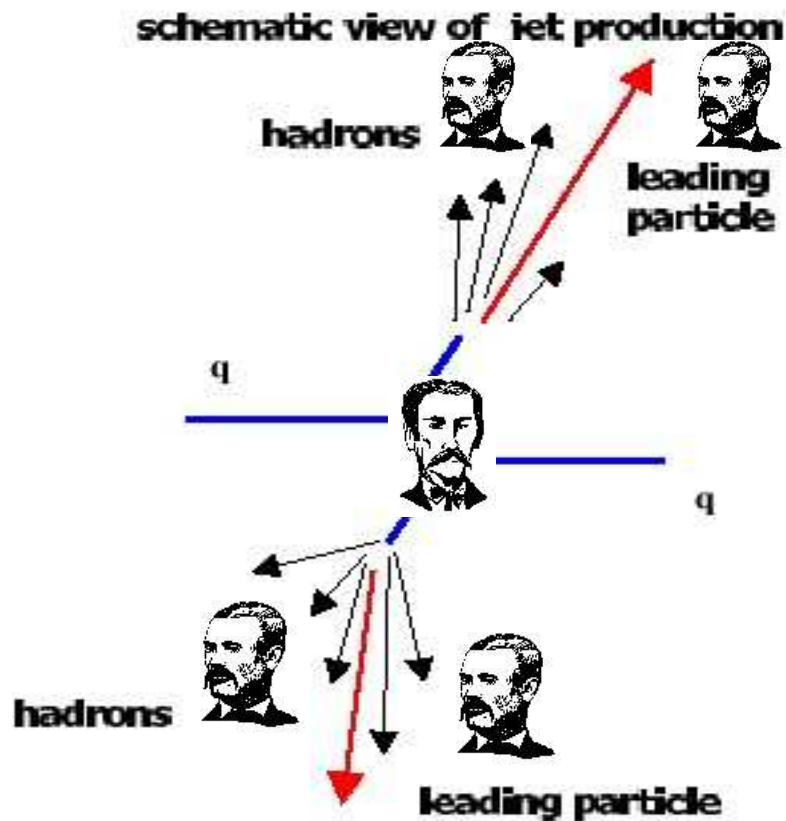


"...HOLD STILL, LARRY. IT'S TAKING ANOTHER PICTURE..."

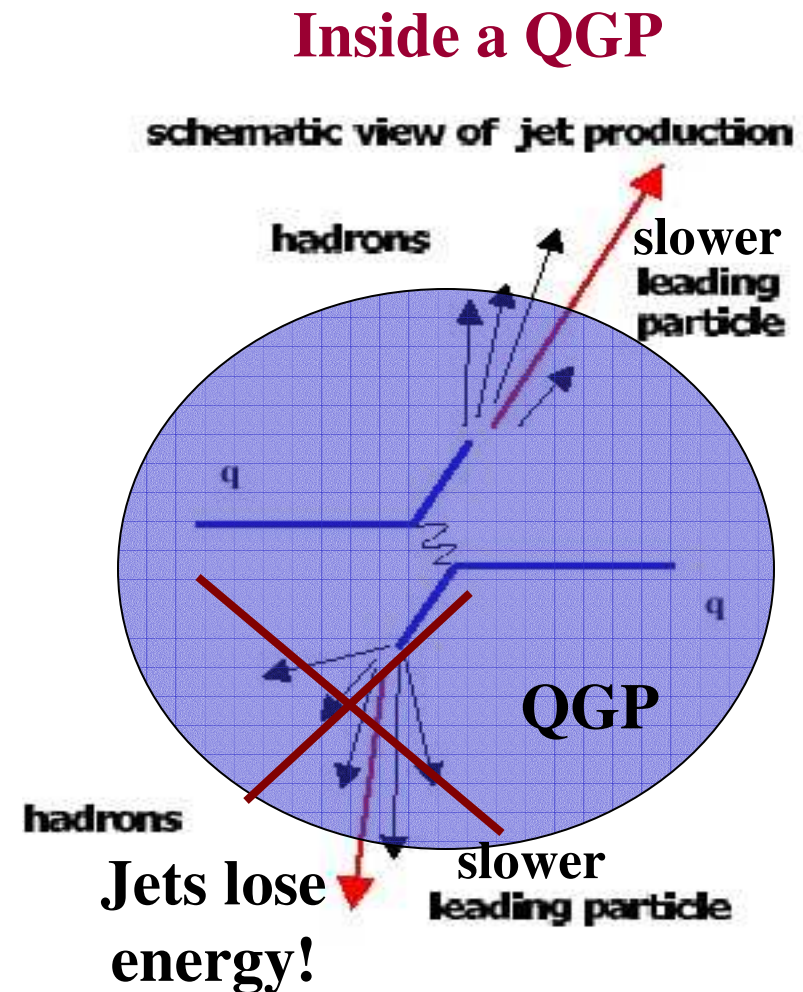
Walt Handelman, New Orleans Times-Picayune

Have we caught a glimpse of the QGP? - Jets

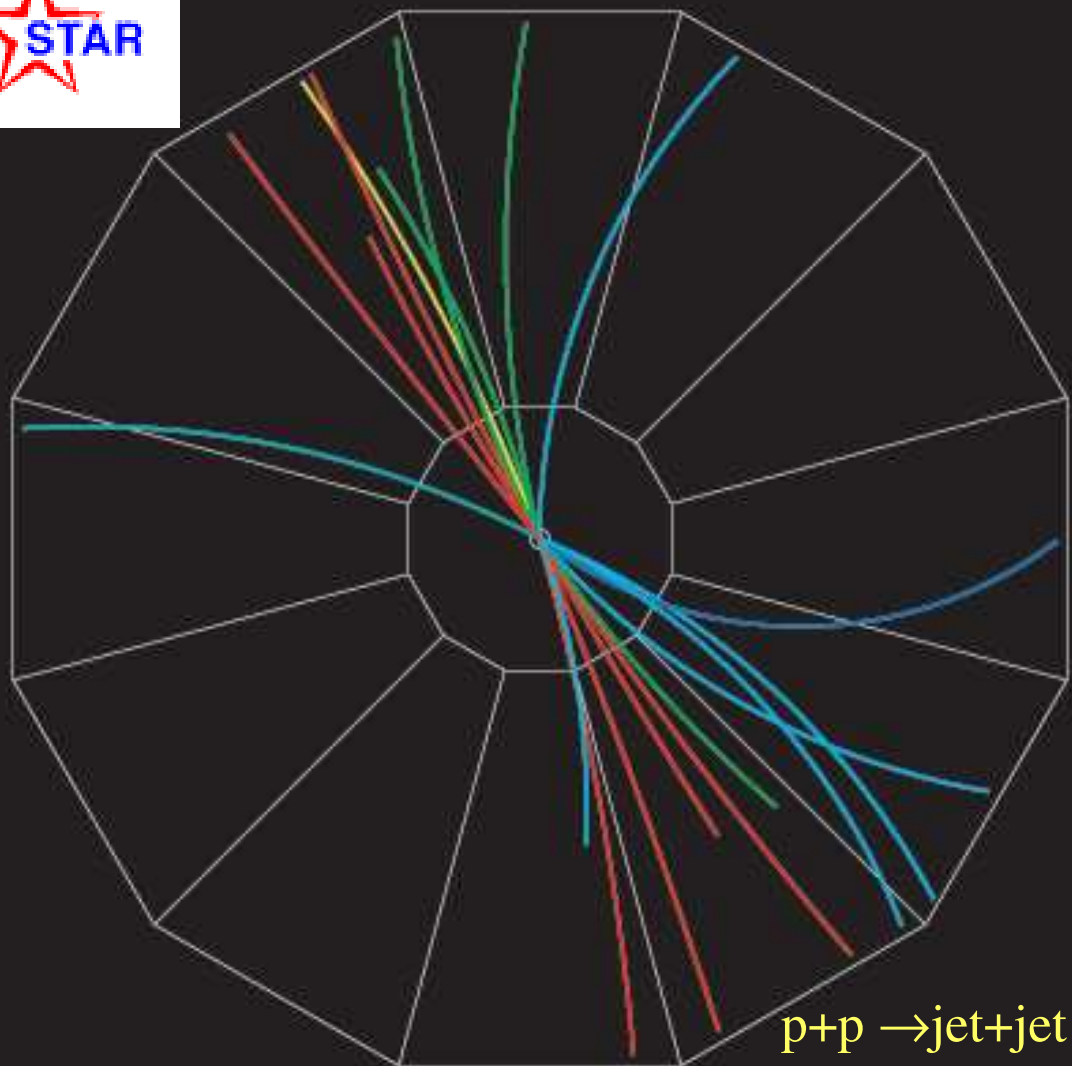
Strategy: Set a trap in the hide-out to slow down escaping jets



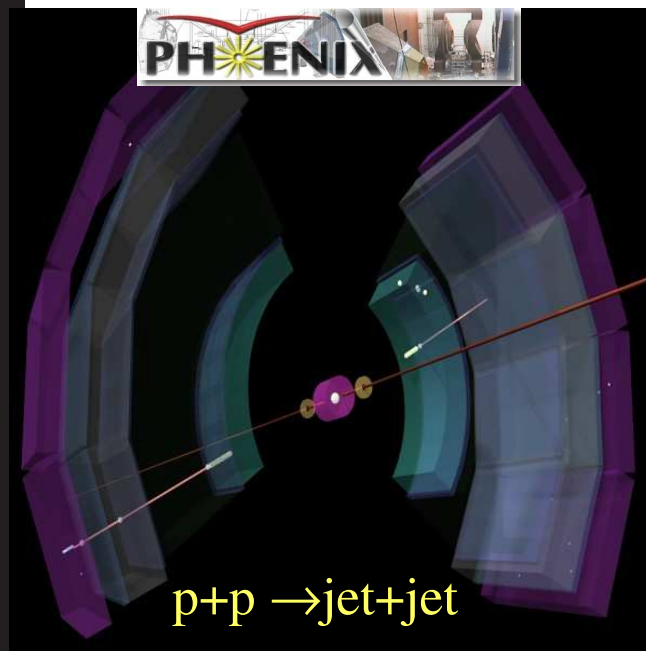
Outside of a QGP



A Jet Seen at RHIC

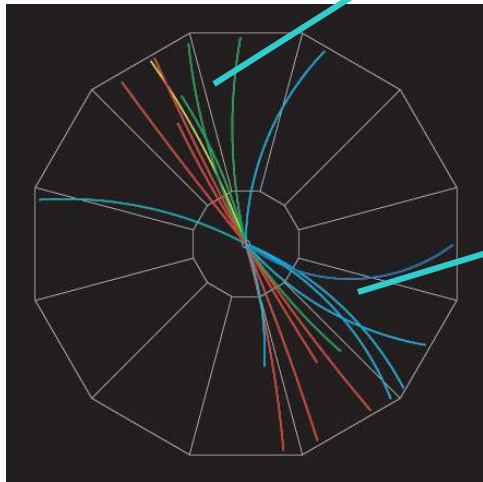
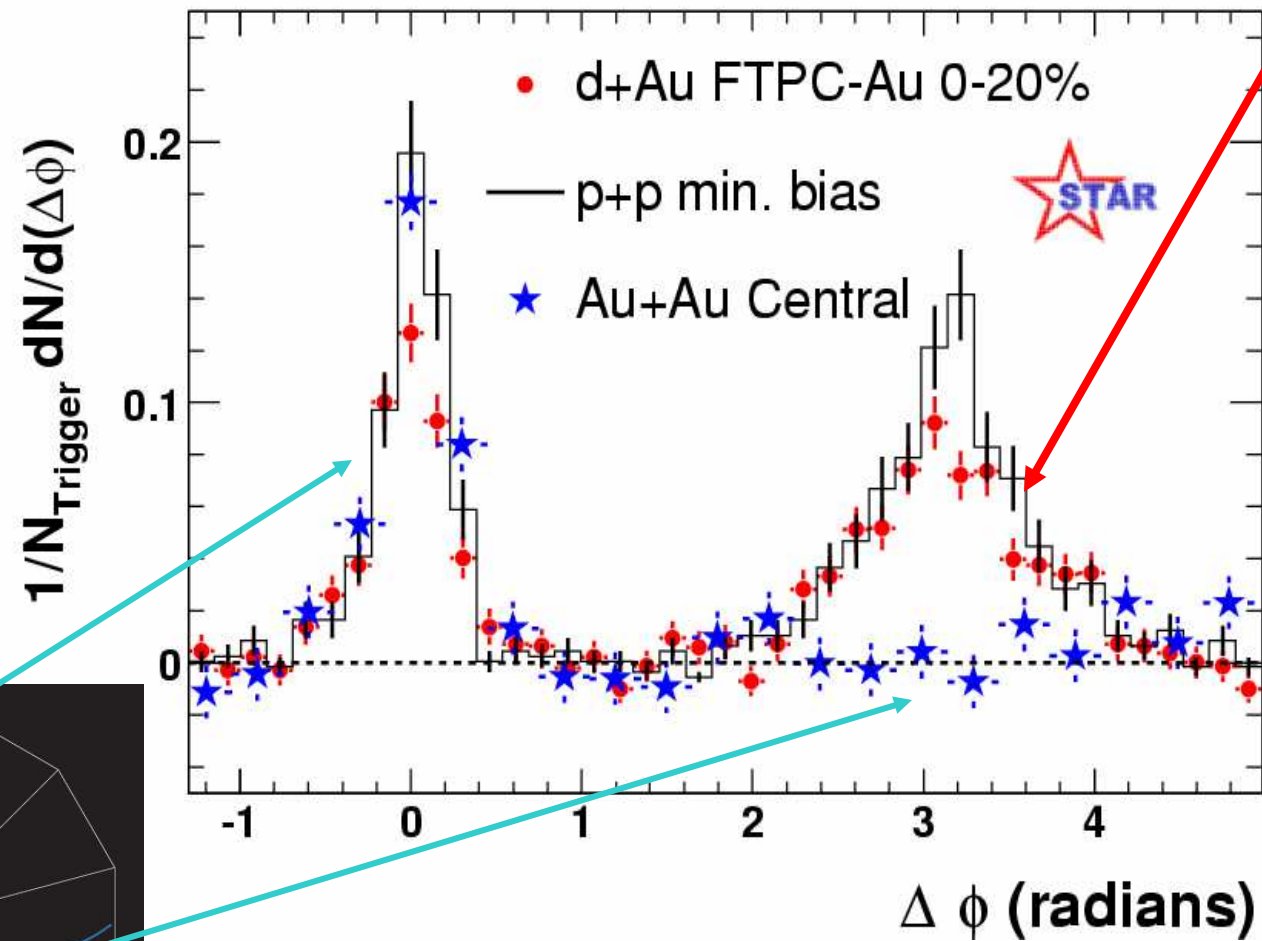


$p+p \rightarrow \text{jet} + \text{jet}$
(STAR@RHIC)

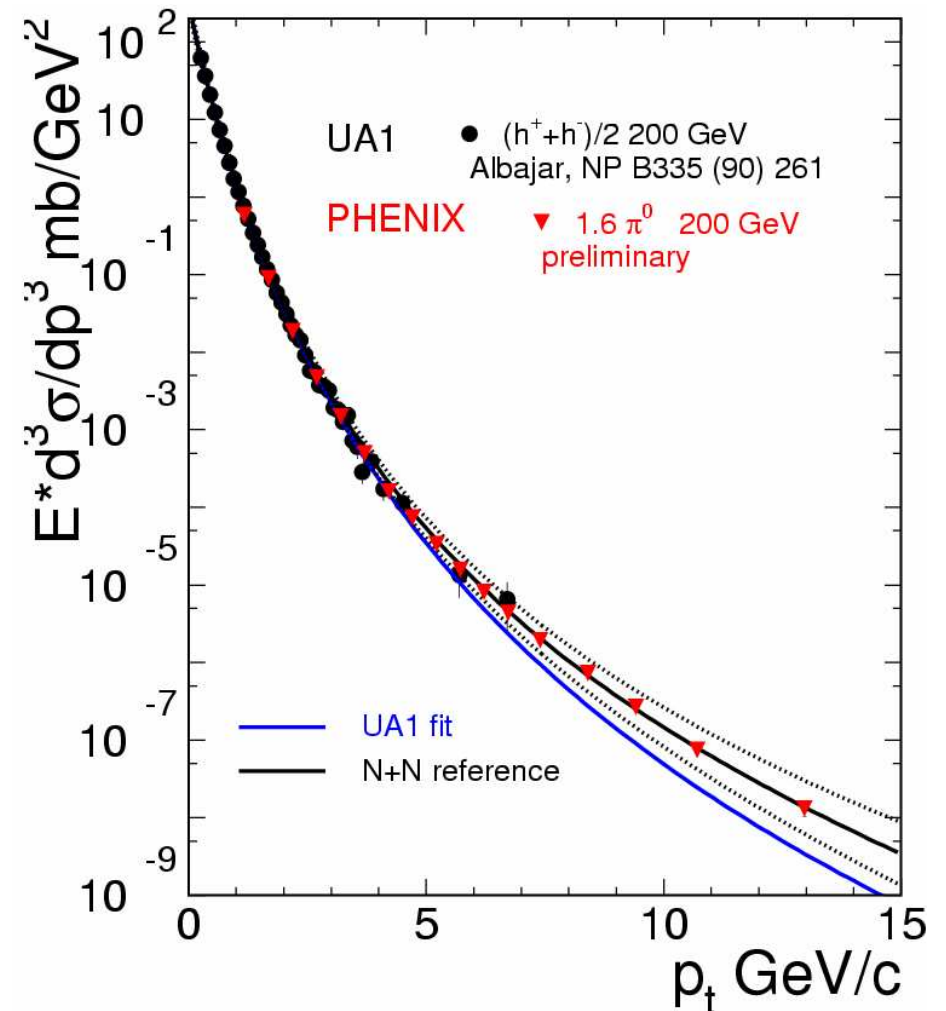
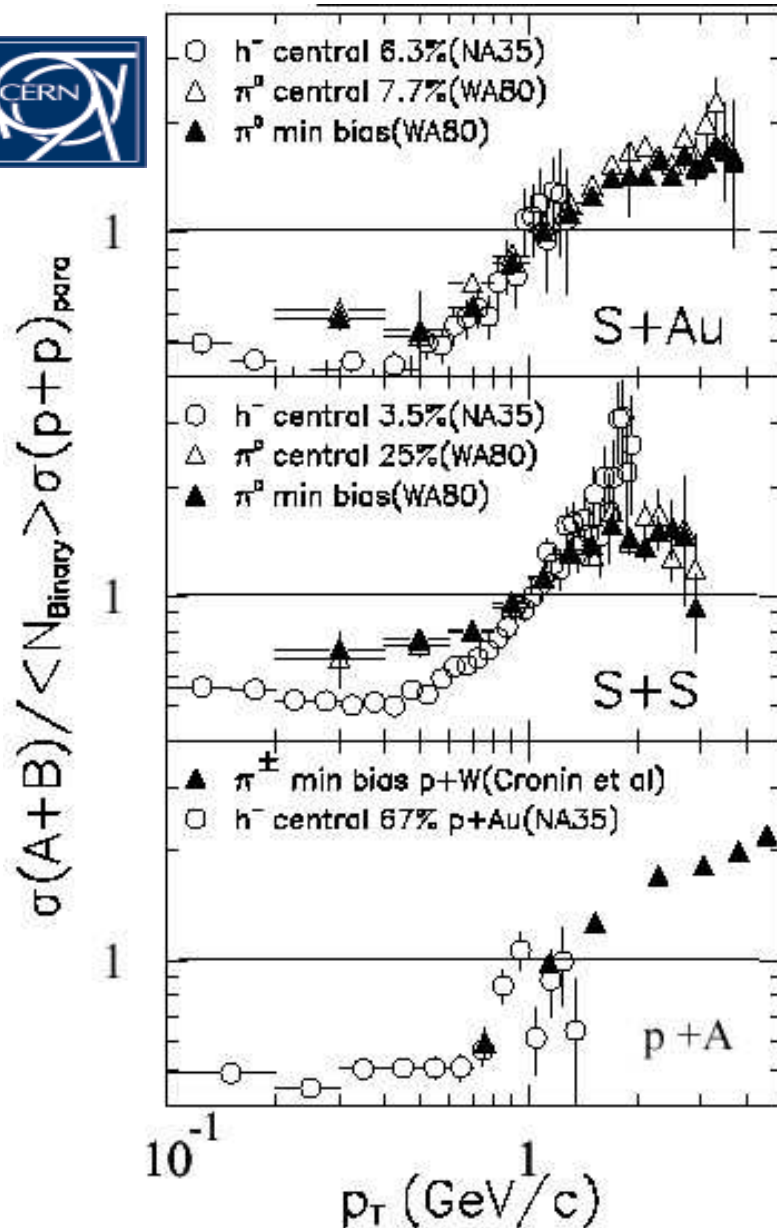


$p+p \rightarrow \text{jet} + \text{jet}$

One Side of the Jet “Disappears” in head-on Au+Au Collisions!



Have we caught a glimpse of the QGP? - Jets



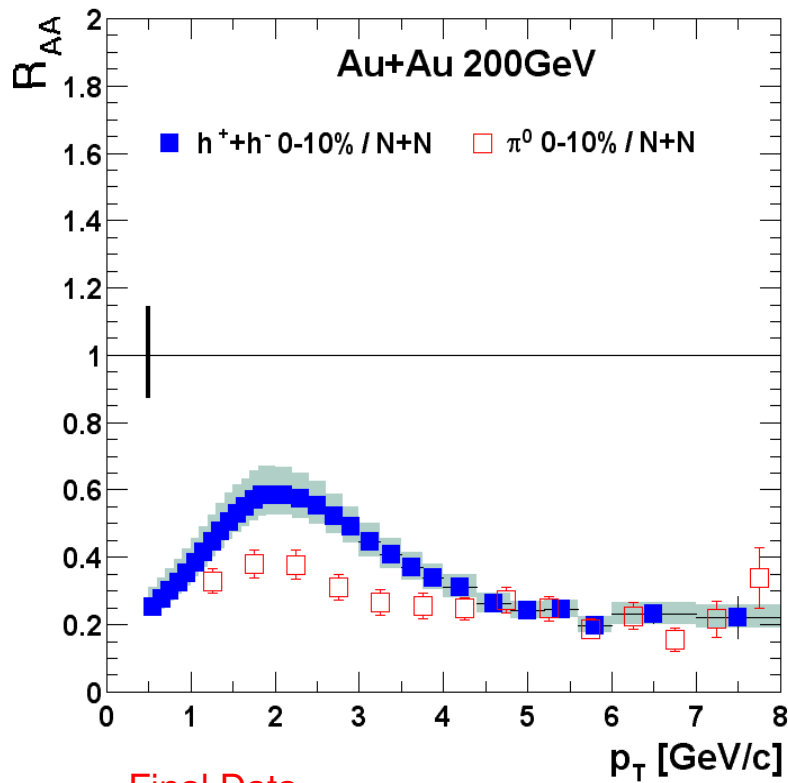
The strategy: Compare particle production to individual proton-proton collisions and look for differences.

Have we caught a glimpse of the QGP? - Jets

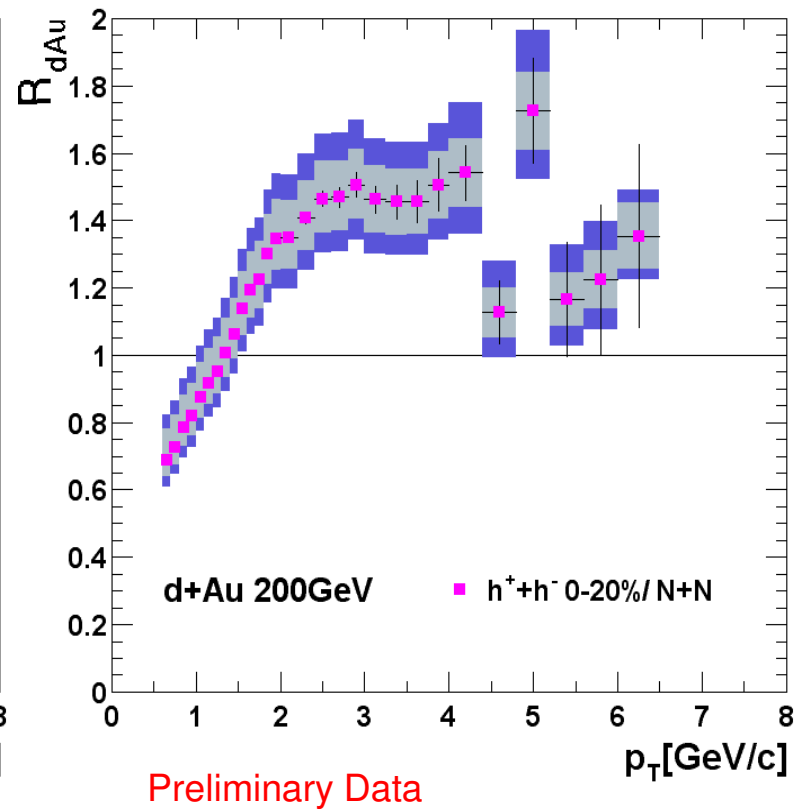
The behavior at RHIC is significantly different!
The control experiment produces significantly different results!



Au + Au Experiment



d + Au Control Experiment



Summary

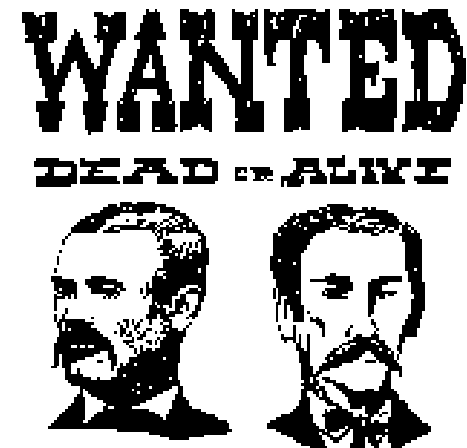
RHIC has taken mass quantities of data in the past 3 years!

Initial analysis of the data shows that the system sets world records in violence, explosiveness, fluidity, and strangeness.

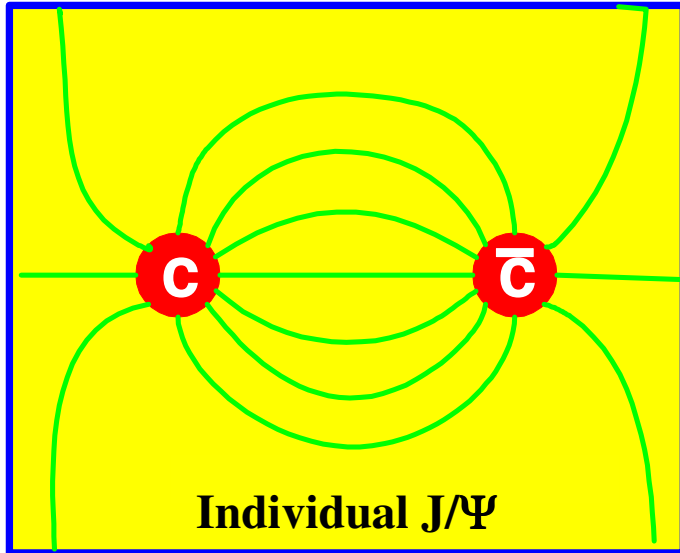
Analysis of high transverse momentum jets prove that there is an energy loss effect that has never been seen before in any particle collision! This effect was predicted to occur in the presence of a Quark-Gluon Plasma!

We are still gathering more evidence and information from jets, photons, muons, electrons, J/Ψ particles, etc.

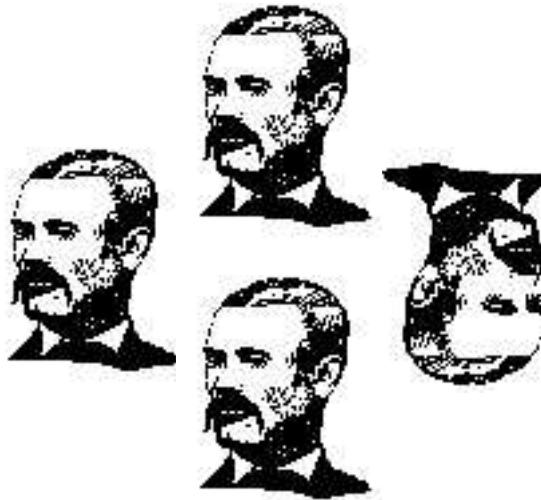
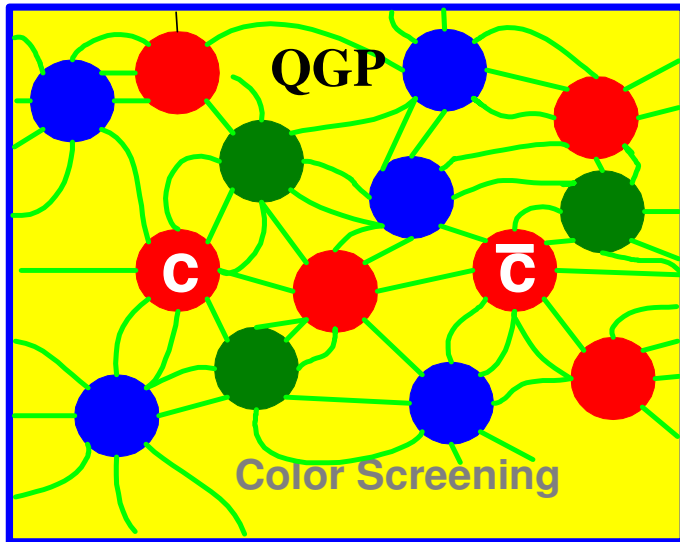
The Quark & Gluon Plasma Brothers
may already be in custody, and we
are bringing them in for further
questioning!



Putting on the Squeeze: J/Ψ Measurements

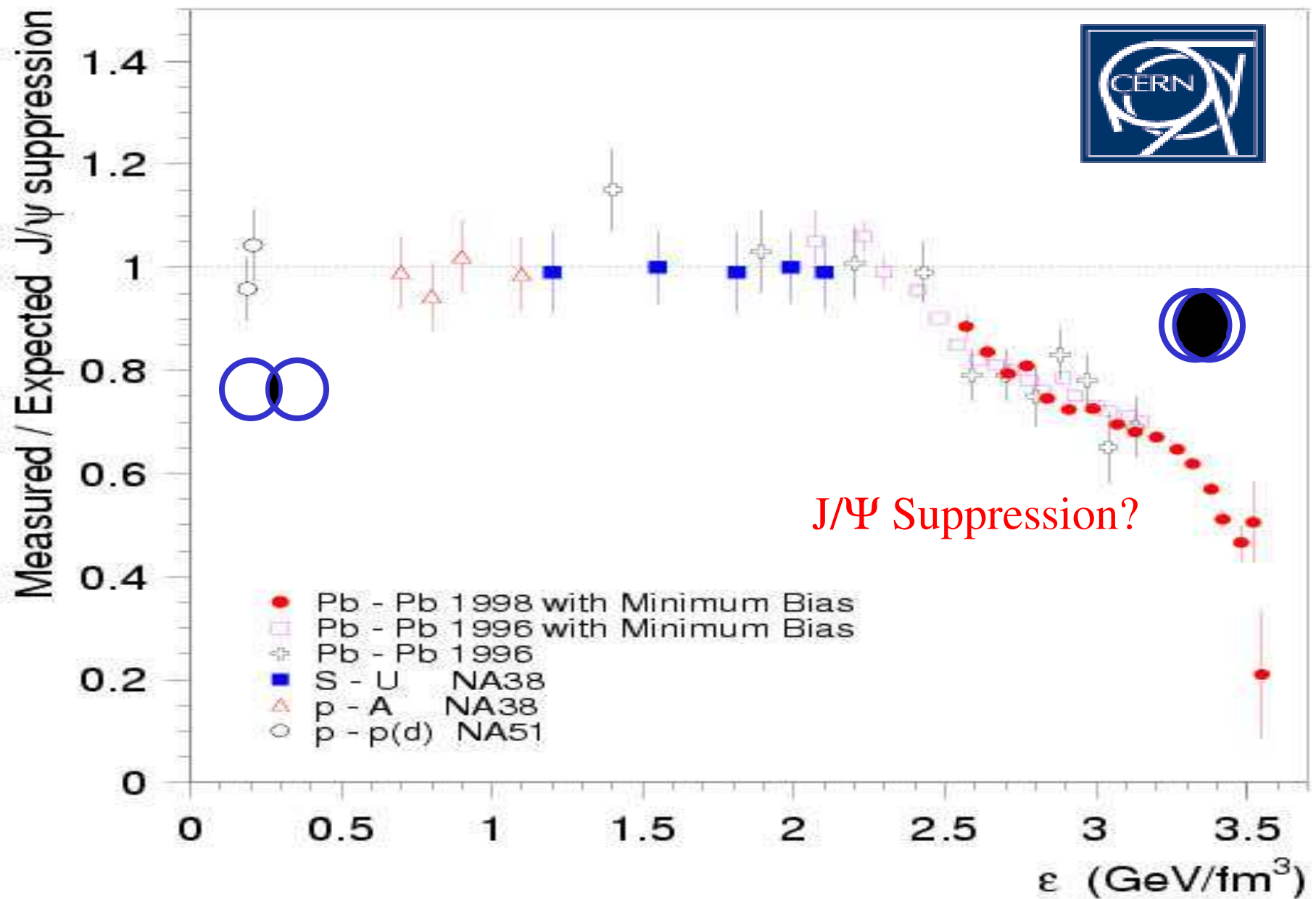


The J/Ψ Particle is a charm + anti-charm pair.



In a QGP, these quarks are “screened” from each other, and J/Ψ particles are suppressed.

Previous J/Ψ Measurements



Electron and Muon Pair Measurements

